Research and Application of 3DVAR&Hybrid Method to Radar Data in Storm Scale

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OUTLINE

I. Recent R&A for stormscale DA

1)Reflectivity data assimilation

2)Weak constraints in 3DVAR

3)Hybrid 3DVAR-EnKF development

4)Realtime ARPS 3DVAR Application

II. Research Challenges & Future Work

I. Recent Research for stormscale DA

1) Reflectivity data assimilation

Previous research:

> 4DVAR technique (Sun and Crook 1997;1998);

> EnKF (Tong and Xue 2005; Dowell, Wicker and Synder, 2011);

> Cloud Analysis method (Alber et al. 1996; Brewster et al. 2005; Hu et al. 2006; Weygandt and Benjamin et al. 2008);

> MM5 3DVAR (Xiao et al. 2005), 3.5VAR (Zhao et al. 2008)

This study is trying to assimilate reflectivity in a unified 3DVAR framework by including ice hydrometeors and partition of hydrometeors using temperature field from NWP model.

(Gao and Stensrud, 2011, *J. Atmos. Sci.* submitted).

Assimilating reflectivity within 3DVAR framework

- First method (1)

  - totoal reflectivity computed as (Smith 1975);

$$Z_e = Z_{er}(q_r) + Z_{es}(q_s) + Z_{eh}(q_h)\ , \qquad (1)$$

- Second method (2)

  – partition reflectivity via temperature from NWP model output.

• T > +5 C: all rain

• T < - 5 C: all snow and hail

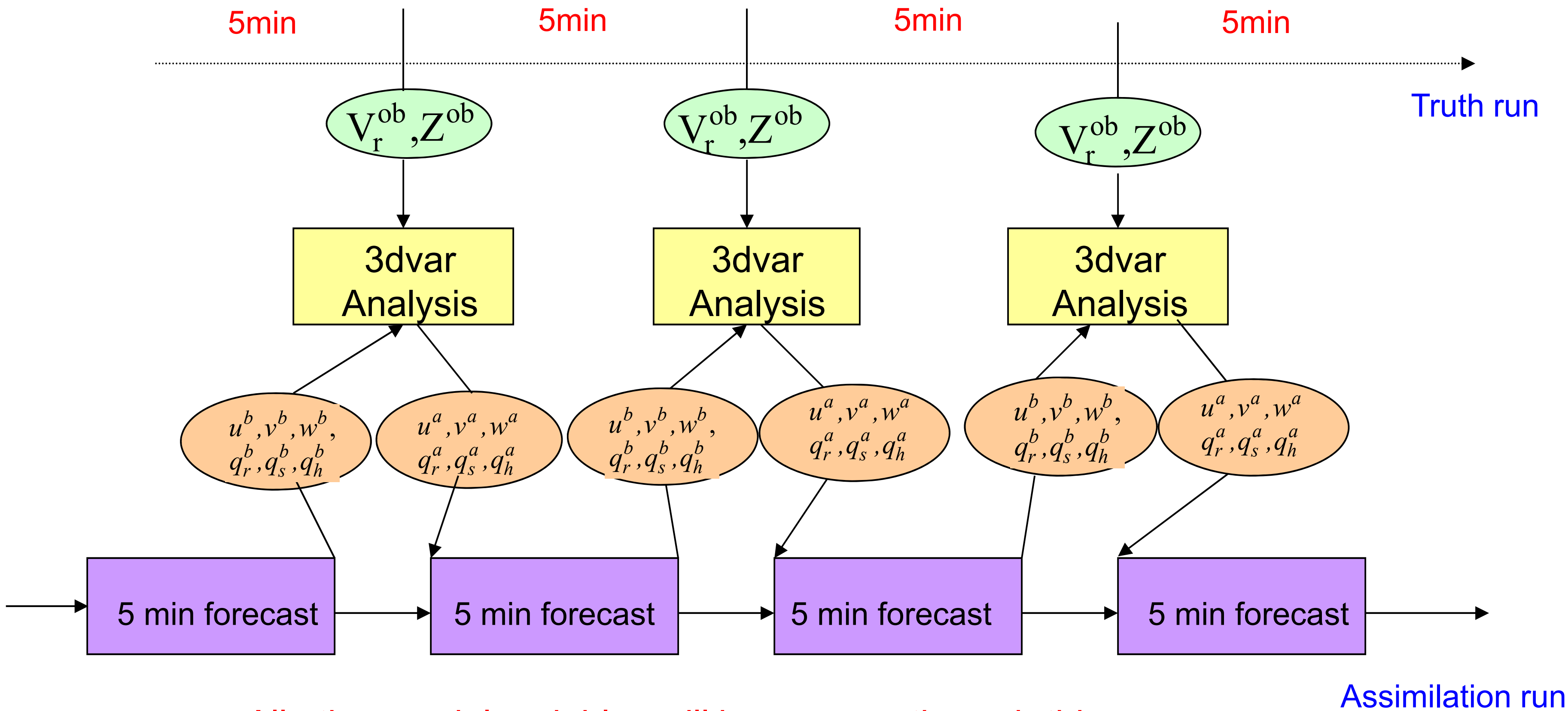
• 5 C > T > -5 C: mixed phase

 - linearly partition reflectivity between rain and ice

.

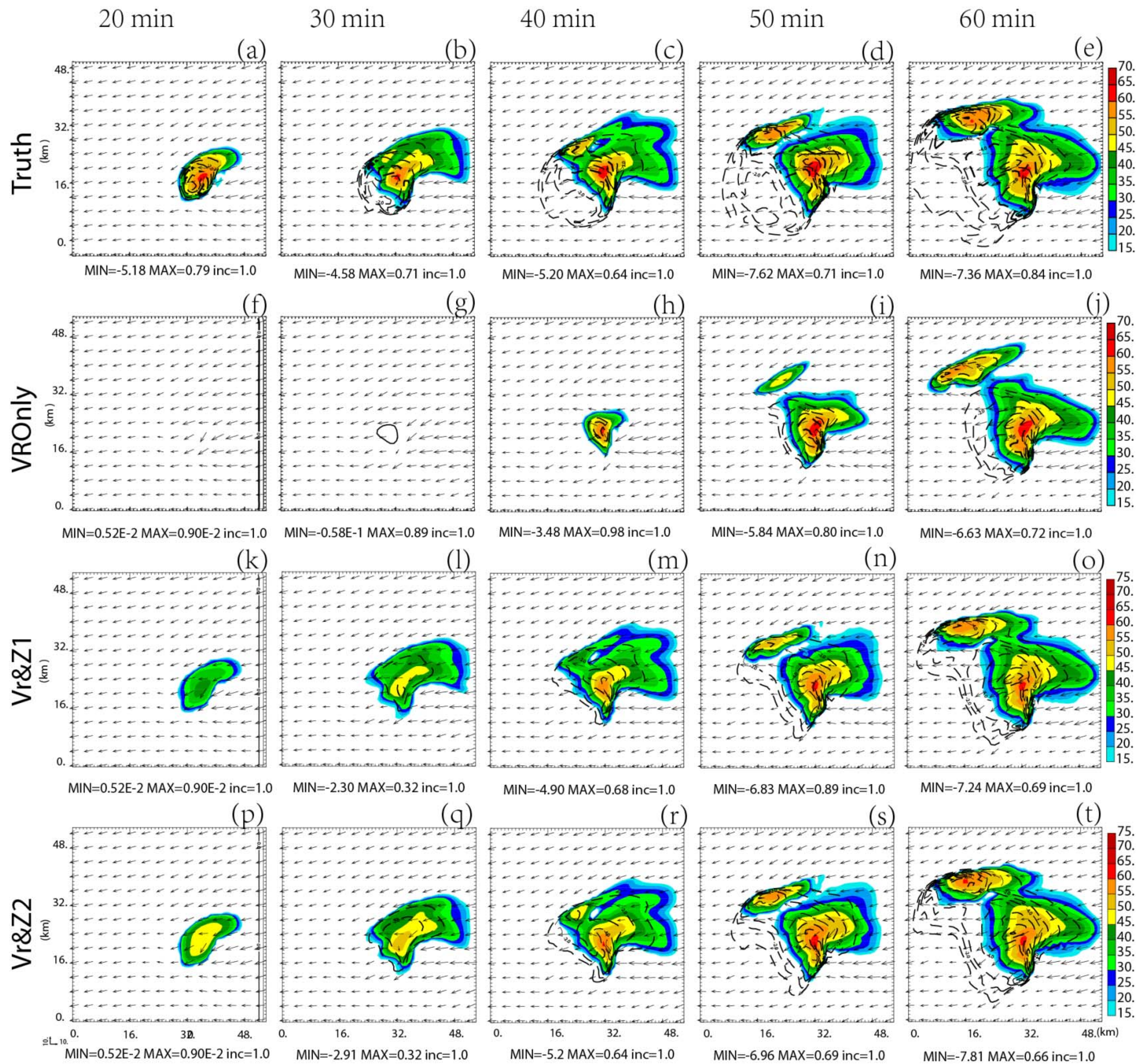
$$Z_e = \begin{cases} Z_{er}(q_r) & T_b > 5^o C \\ Z_{es}(q_s) + Z_{eh}(q_h) & T_b > -5^o C \\ \alpha Z_{er}(q_r) + (1-\alpha)\left[Z_{es}(q) + Z_{eh}(q)\right] & -5^o C < T_b < 5^o C \end{cases} \qquad (2)$$

Continuous cycles of radar data assimilation



All other model variables will be spun up through this process

The initial idea was proposed by Charney et al. (*J. Atmos. Sci.*, 1969) to assimilate satellite data; Daley (1992) named it as "continuous (frequent) forward data assimilation" method.



5 min cycled 3dvar analysis

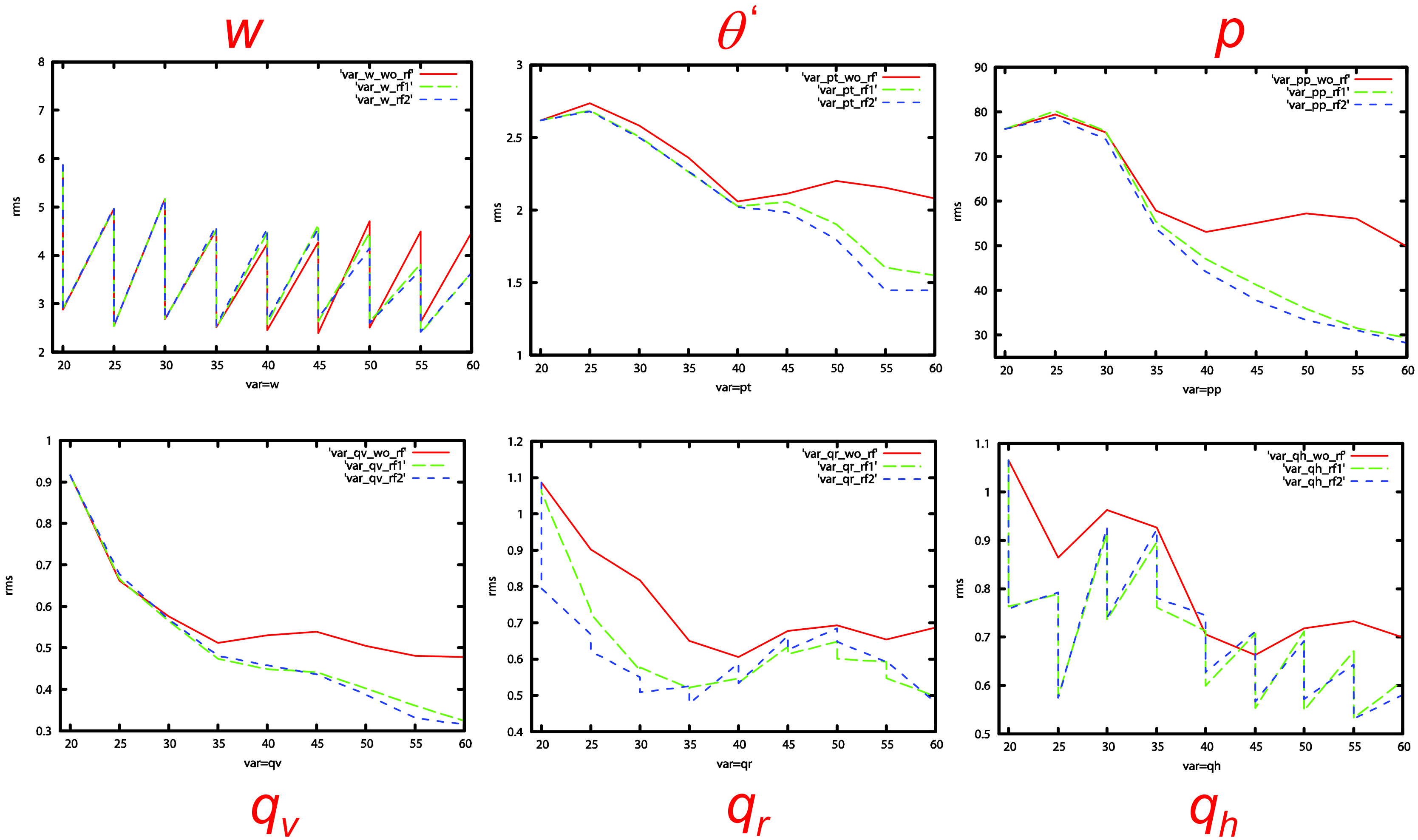
For an idealized Case

Z (shaded)

V (vectors)

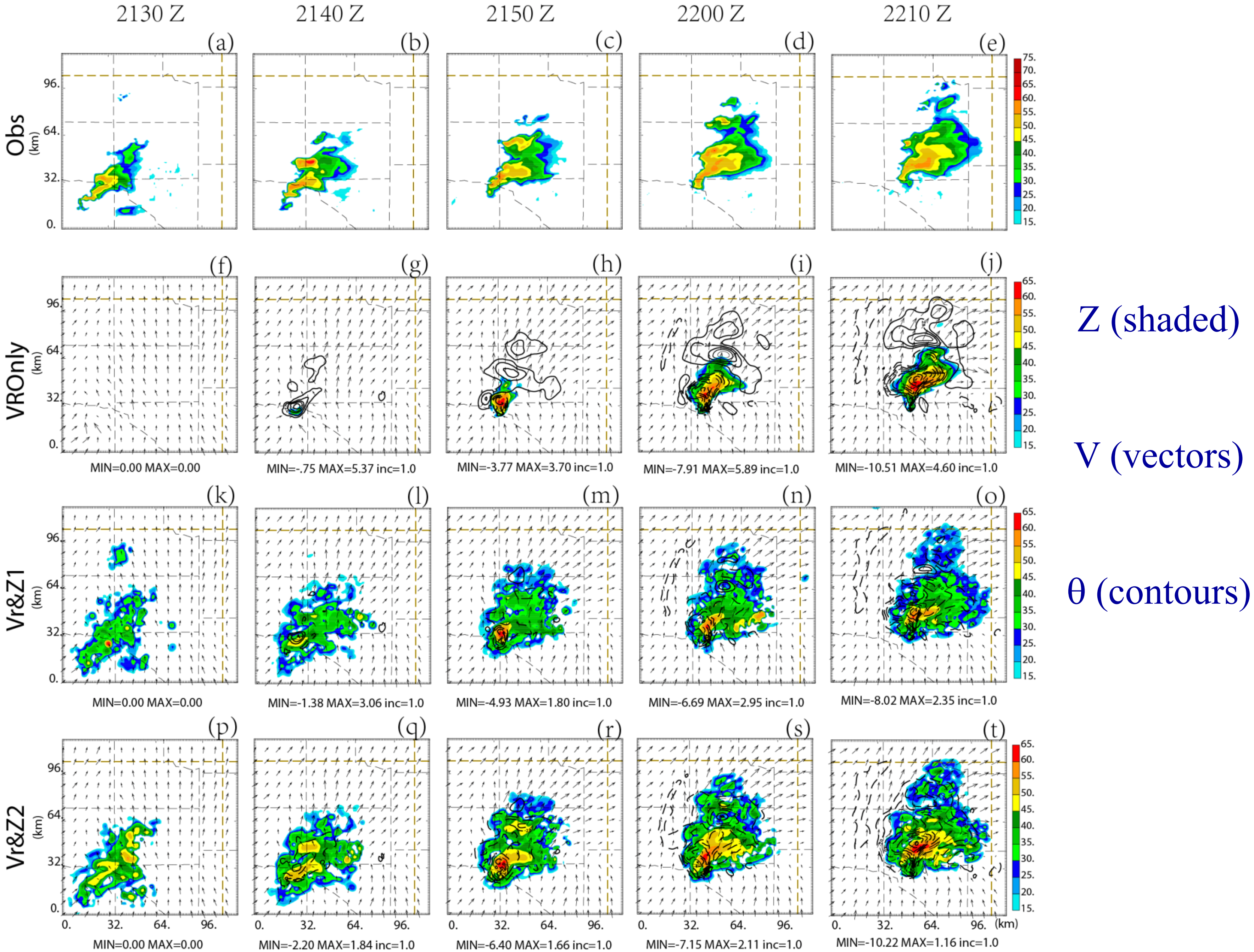
θ (contours)

RMS Errors of the Analyses for 6 model variables

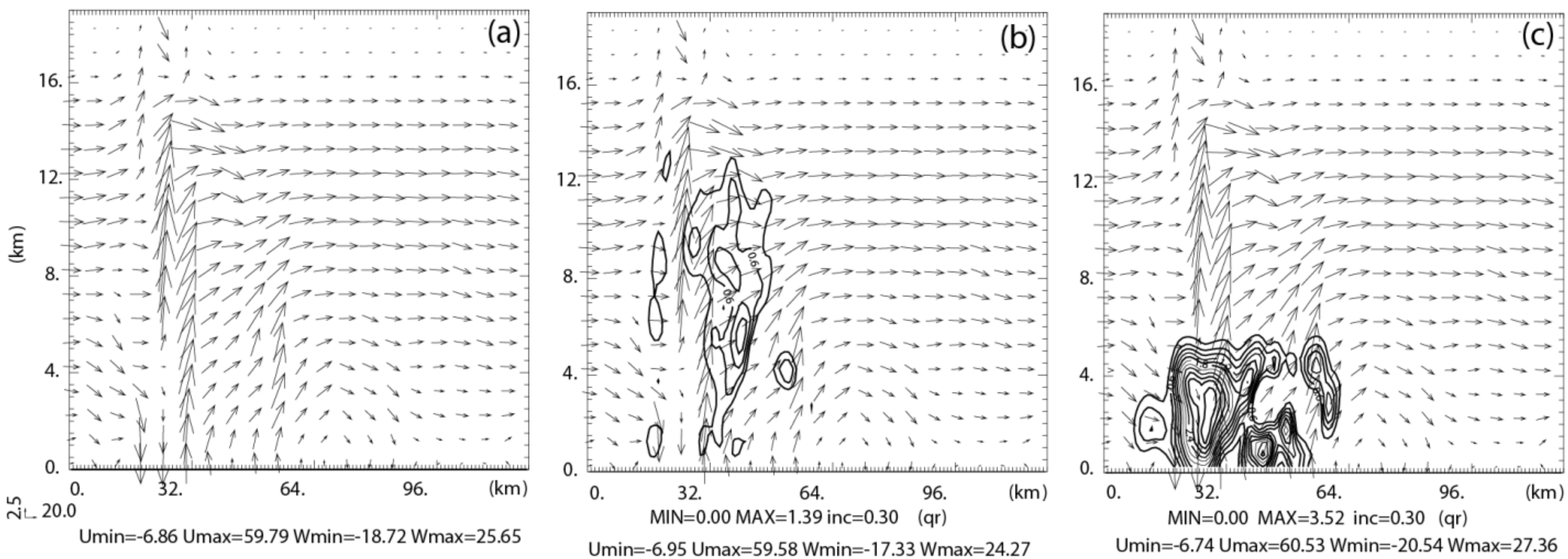


Red real line is for Vr only; dashed green is for Vr&Z(1) and the dashed blue is for Vr&Z(2)

May 8, 2003 OKC Tornadic Supercell case



Vr Only   Vr & Z (1)   Vr & Z (2)



A x-z vertical slice for V (m s^{-1}), qr (contours)

At 2130 UTC, 8 May 2003 OKC supercell storm

2) Weak constraints in 3DVAR

Gao et al. 1999, 2004; Hu et al. 2006; Ge et al. 2010; 2011

Protat and Zawadzki 2000; Weygandt 2002a,b; Xu et al. 2003, 2009

$$J(x) = \frac{1}{2}(x - x^b)^T B^{-1}(x - x^b) + \frac{1}{2}\left[H\left(x\right) - x^o\right]^T R^{-1}\left[H\left(x\right) - y^o\right] + J_c(x)$$

$$J_c = P(x)^T A_P^{-1} P(x) + Q(x)^T A_Q^{-1} Q(x)$$

$$Q = \frac{\partial \overline{\rho} u}{\partial x} + \frac{\partial \overline{\rho} v}{\partial y} + \frac{\partial \overline{\rho} w}{\partial z}$$

$$P \equiv \nabla \cdot \vec{E} \equiv -\nabla^2 p' - \nabla \cdot (\overline{\rho}\vec{V} \cdot \nabla \vec{V}) + g\frac{\partial}{\partial z}\left(\overline{\rho}\left[\frac{\theta'}{\overline{\theta}} - \frac{p'}{\overline{\rho} c_s^2} + \frac{q_v'}{\varepsilon + \overline{q}_v} - \frac{q_v' + q_{liquid+ice}}{1 + \overline{q}_v}\right]\right) + \nabla \cdot \vec{C} + \nabla \cdot \vec{D}$$

$$\vec{E} = \frac{\partial\left(\overline{\rho}\vec{V}\right)}{\partial t} = \vec{i}\frac{\partial\left(\overline{\rho}u\right)}{\partial t} + \vec{j}\frac{\partial\left(\overline{\rho}v\right)}{\partial t} + \vec{k}\frac{\partial\left(\overline{\rho}w\right)}{\partial t} \qquad \vec{V} = \vec{i}u + \vec{j}v + \vec{k}w$$

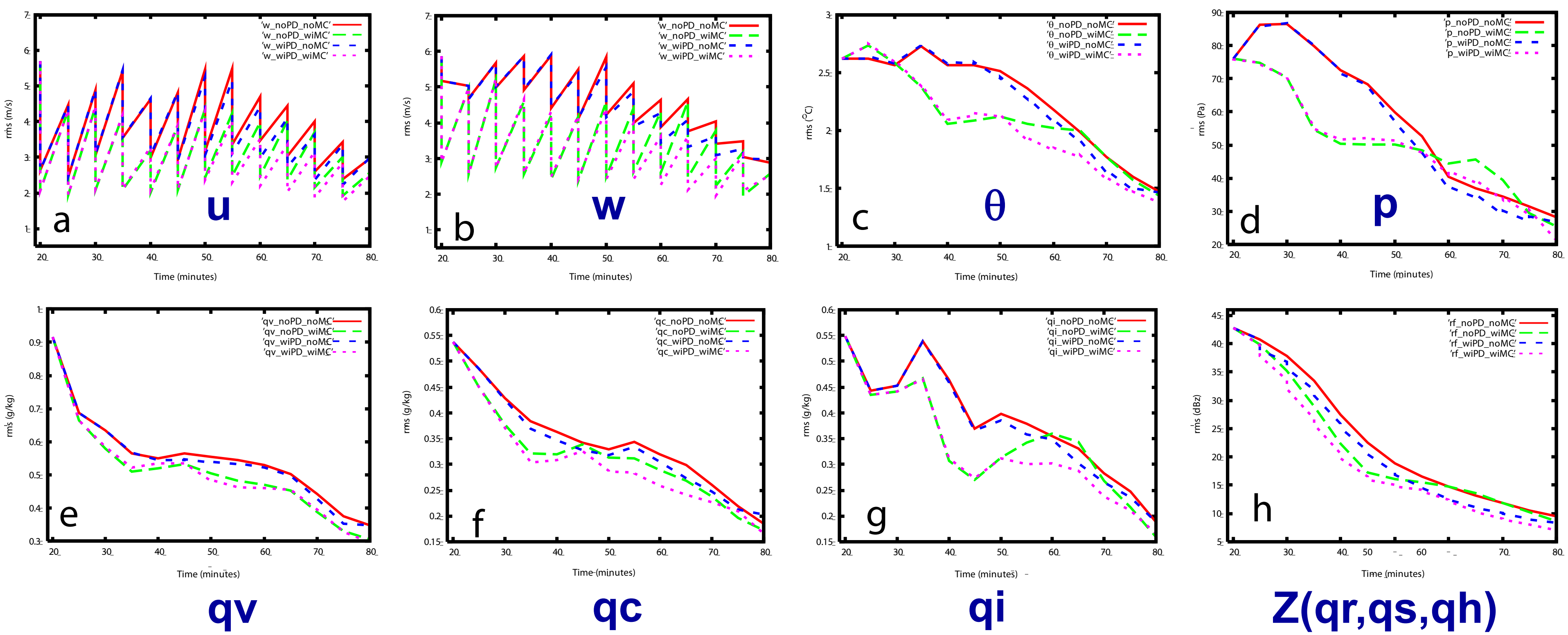
$$\vec{C} = \vec{i}\left(\overline{\rho}fv - \overline{\rho}\tilde{f}w\right) + \vec{j}\left(\overline{\rho}fu\right) + \vec{k}\left(\overline{\rho}\tilde{f}u\right) \qquad \vec{D} = \vec{i}D_u + \vec{j}D_v + \vec{k}D_w$$

The main goal of adding **equation constraints** is to help **improve balance** between different model variables.

Idealized Case

RMS Errors of the Analyses for 8 model variables

NoEQ; MC_Only; PD_Only; MC_PD

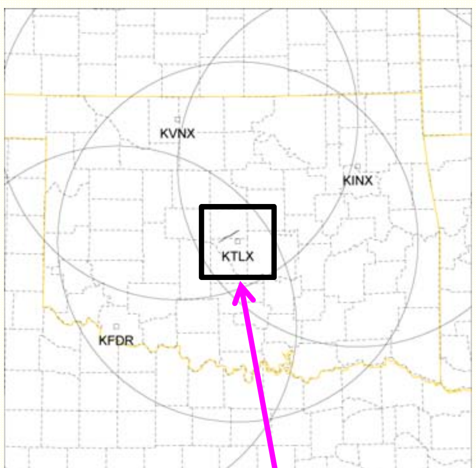


MAY 08, 2003 case

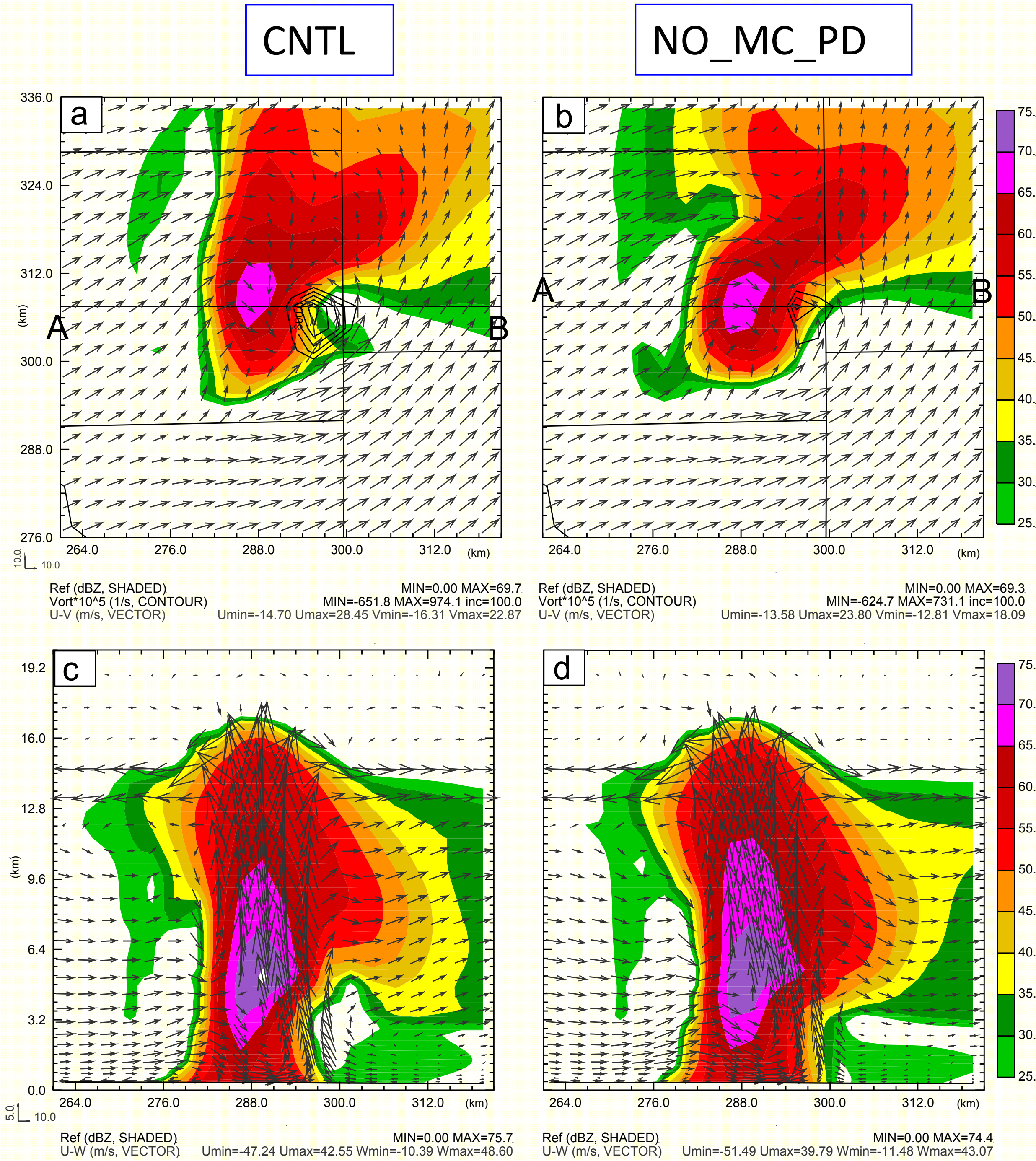
40 min forecast

The reflectivity, wind At 2220UTC for Z=3km MSL and y=307.5km

576X576 km^2

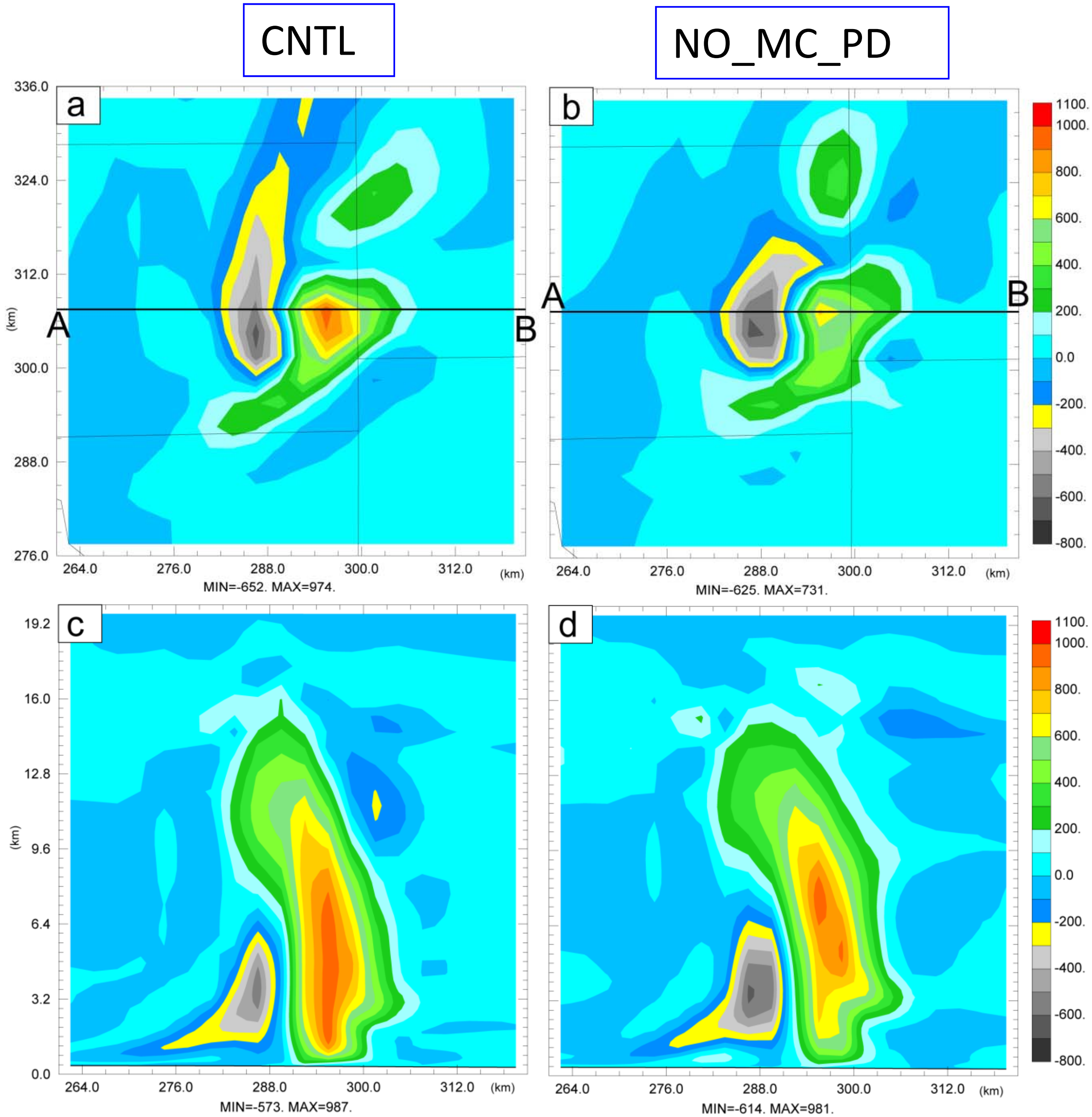


60X60 km^2



The vertical vorticity At 2220UTC

for Z=3km MSL and y=307.5km



3) Hybrid EnKF & 3DVAR development

- Hybrid 3(4)DVAR/EnKF may optimally combine dynamic and statistical information.
- For storm scale, first guess/model error can be very large! Statistical representation of dynamics can be completely wrong.
- Including static B may help stabilize the analysis (not driven too much by the model).
- Hybrid systems can be easily built based on existing ensemble and variational frameworks (Hamill and Synder 2000; Lorenc 2003; Wang et al. 2007, 2009).

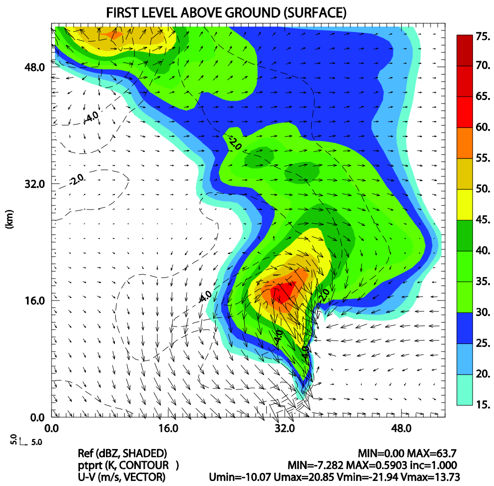
List of OSSE with pure 3DVAR, pure EnKF and hybrid 3DVAR-EnKF

Experiment	Description
EXP1	Pure 3DVAR at HR (1 km)
EXP2	Pure EnKF at HR (1 km)
EXP3 EXP4	Hybrid EnKF-3DVAR at HR (1 km) Hybrid EnKF-3DVAR at DR (1 & 4 km)

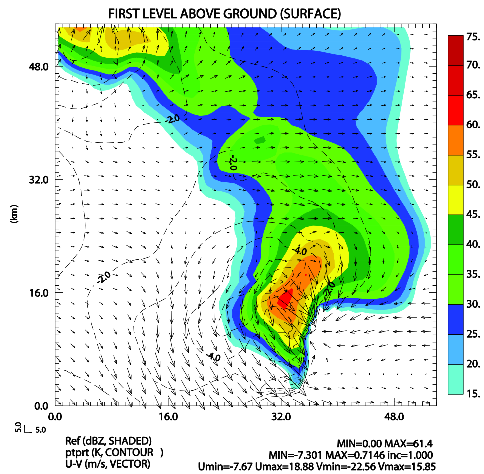
The simulated Vr & Z are from single radar

θ'(contours), Z(color shades) and V_h (vectors) at Surface

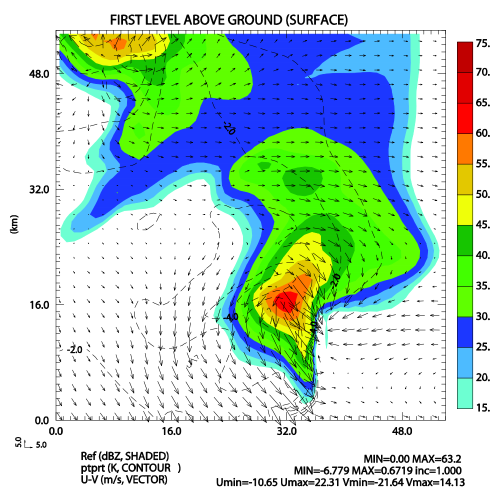
after 60 Min. DA Cycles



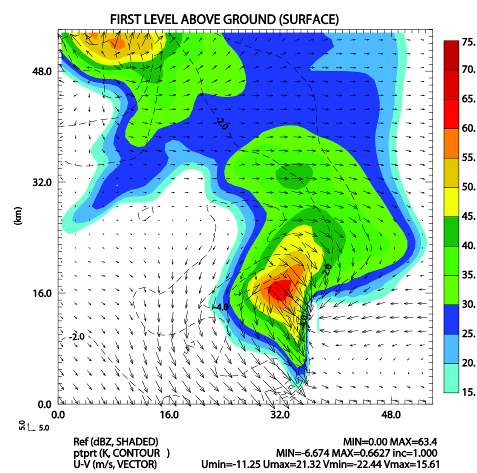
Truth



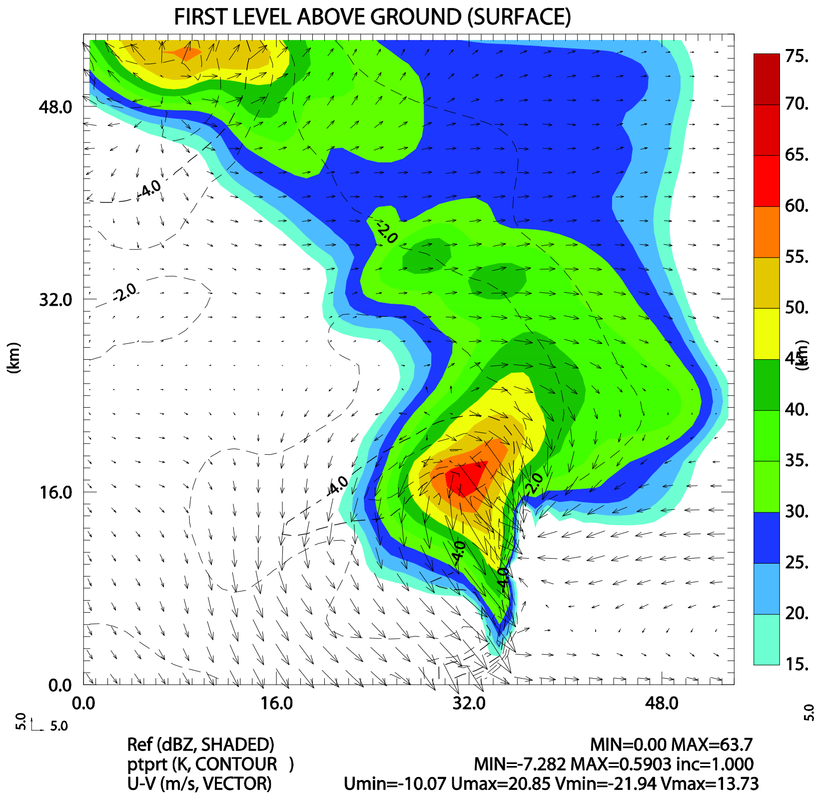
Pure 3DVAR (EXP1)



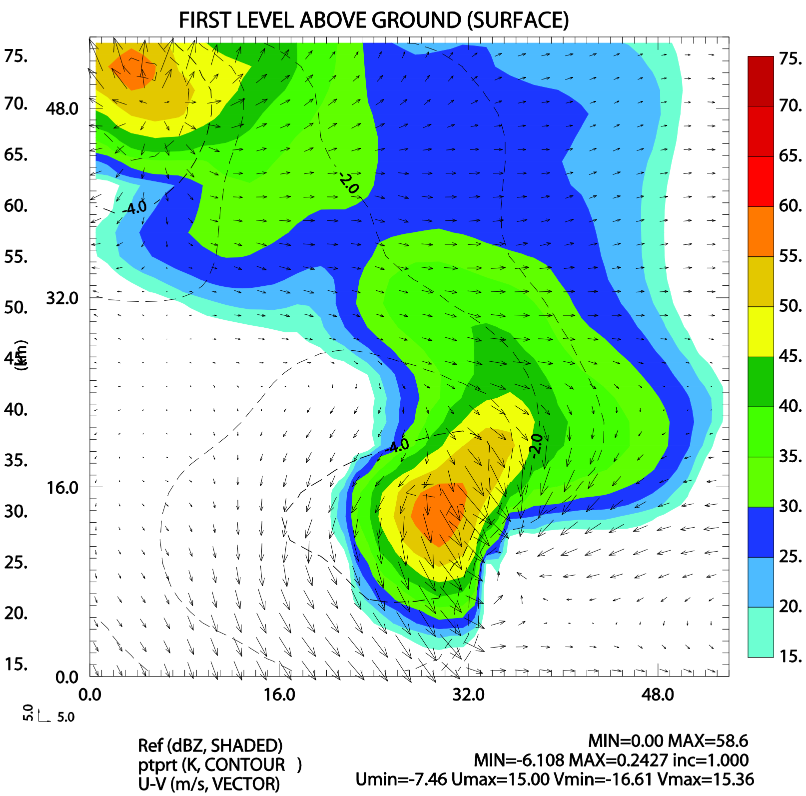
Pure EnKF (EXP2)



EnKF-3DVAR (EXP3)



Truth



EnKF-3DVAR

(Dual-resolution EXP4)

4) Realtime ARPS 3DVAR Application

- To create realtime weather-adaptive 3DVAR analyses at high horizontal resolution (1km) & high time frequency (5 min) with all operationally available radar data from the 88D network.
- To use the analysis product to help detect supercells and determine if these analyses can improve forecasters’ awareness of the hazardous weather threat.

Ingredients

I. WDSS-II real-time 2D composite reflectivity product.
II. NCEP NAM NWP product (0-9 hrs).
III. Radar data from national 88D network.
III. Some types of surface data.
IV. ARPS 3DVAR and related pre- and post-processing programs.

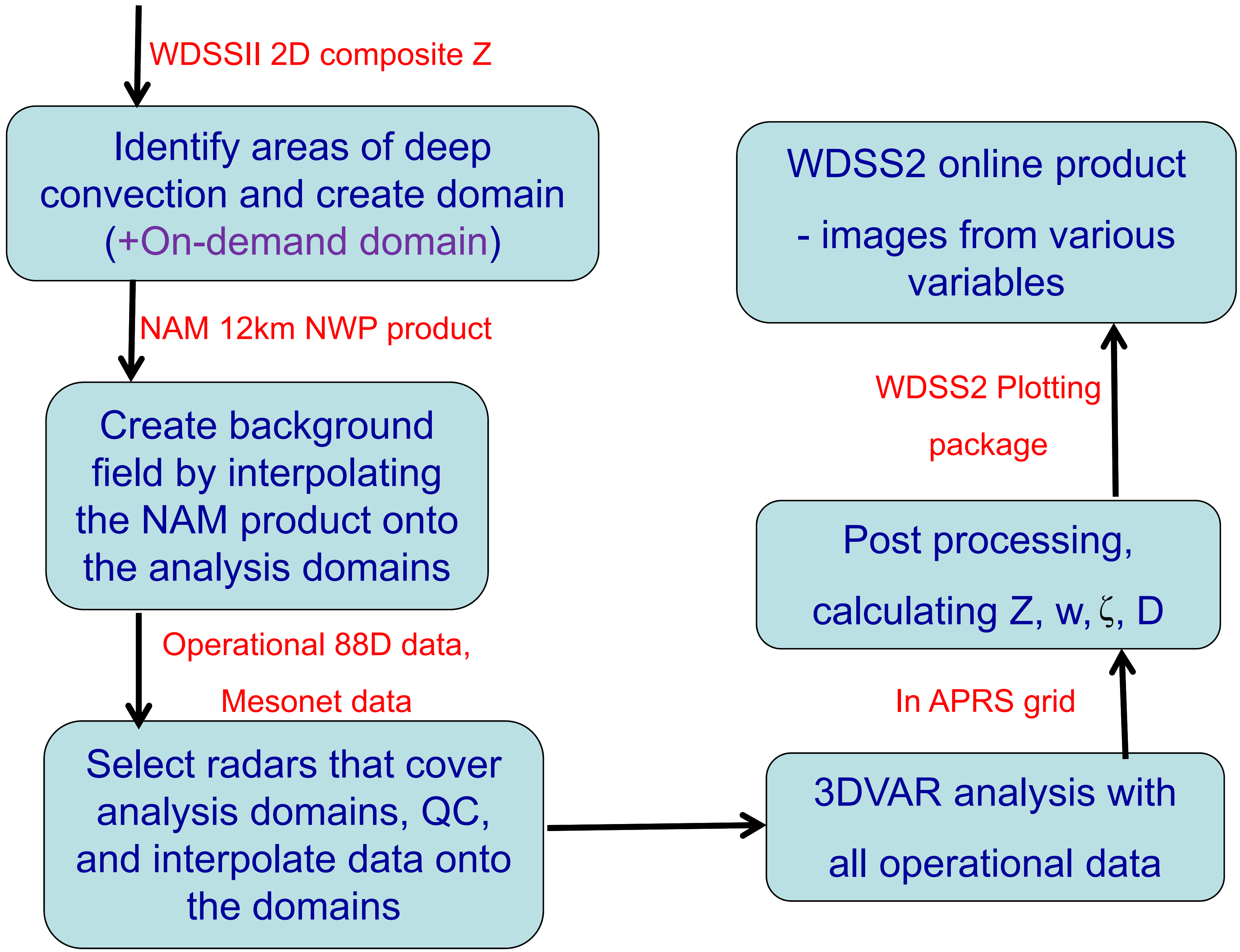
Feasibility

- WSR-88D coverage is pretty good for vertical levels between 3 and 5 km from Midwest to Eastern US (so good for mesocyclone detection).

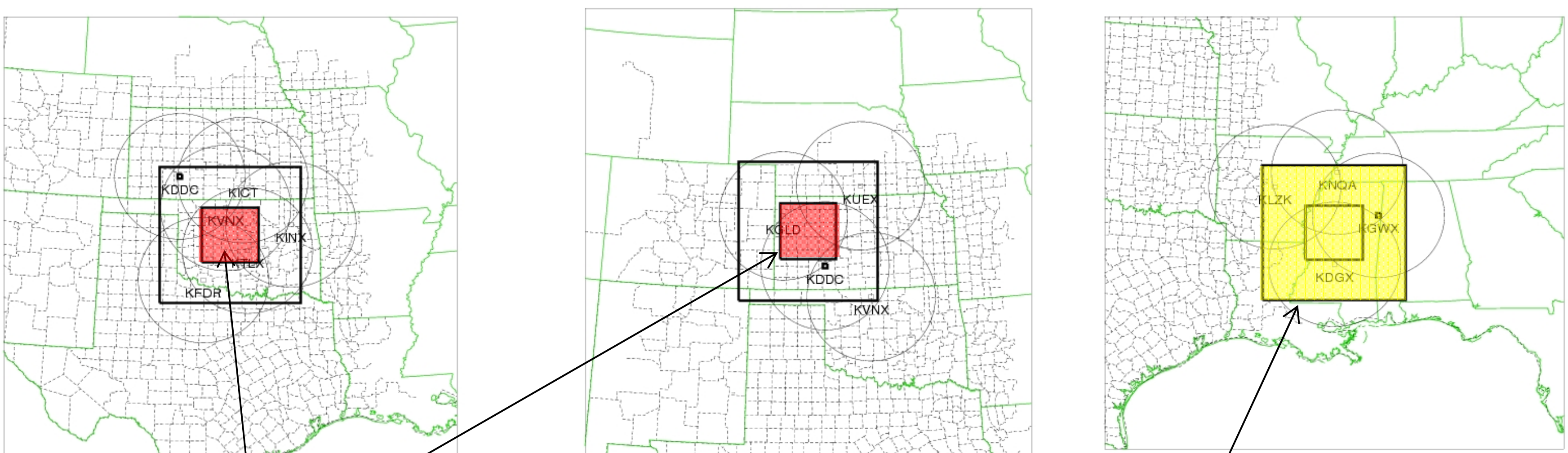
from McLaughlin et al. 2009

- NCEP NAM NWP products provide storm environment as accuracy as sounding (often overlooked by people!).
- ARPS 3DVAR is computationally very efficient, and was designed for storm-scale.

Flow Chart of the weather-adaptive 3dvar System



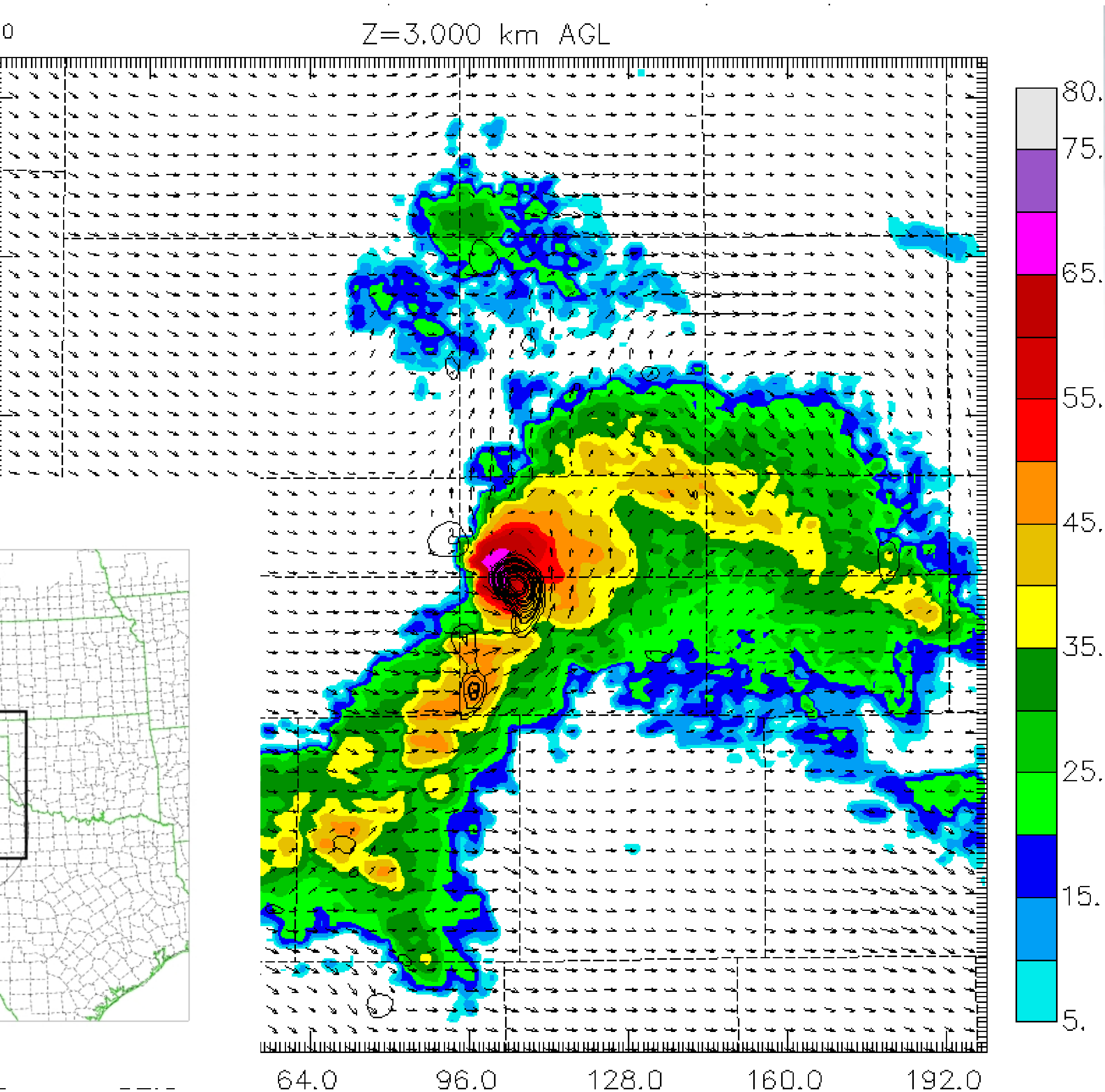
Example Domains

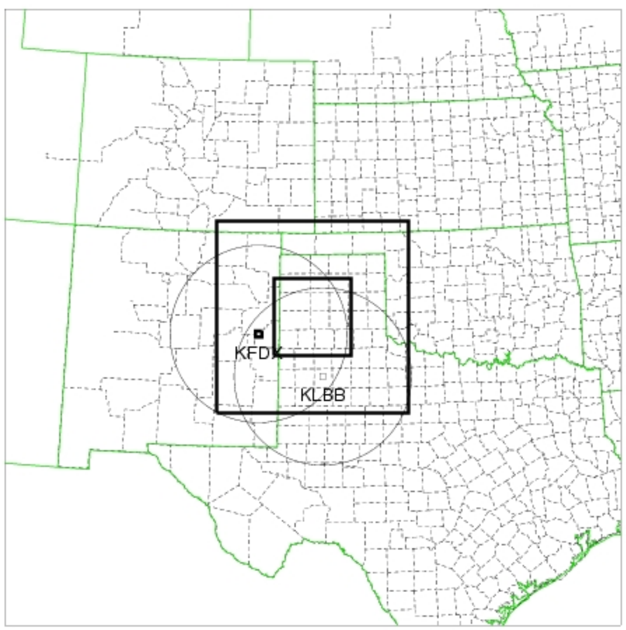


Inner domain of 200x200 km is used for 3dvar analysis

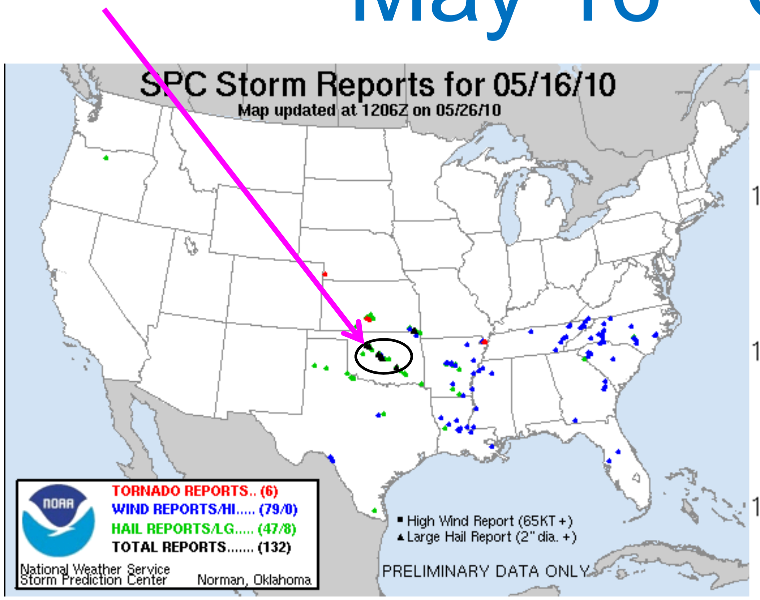
Outer domain of 400x400 km is used to identify 88Ds to be used

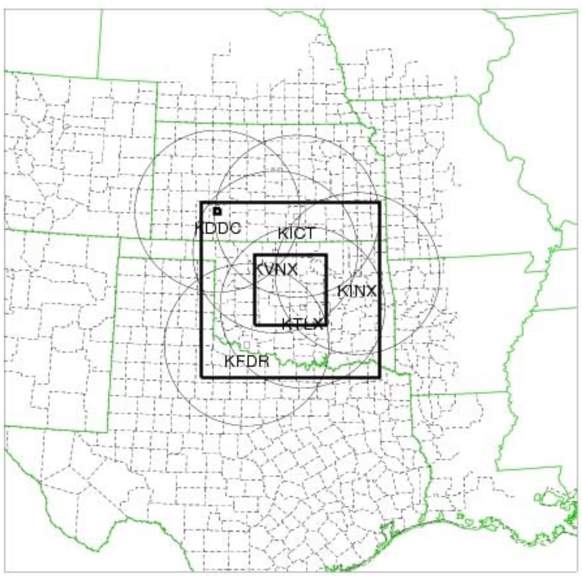
Example Analysis

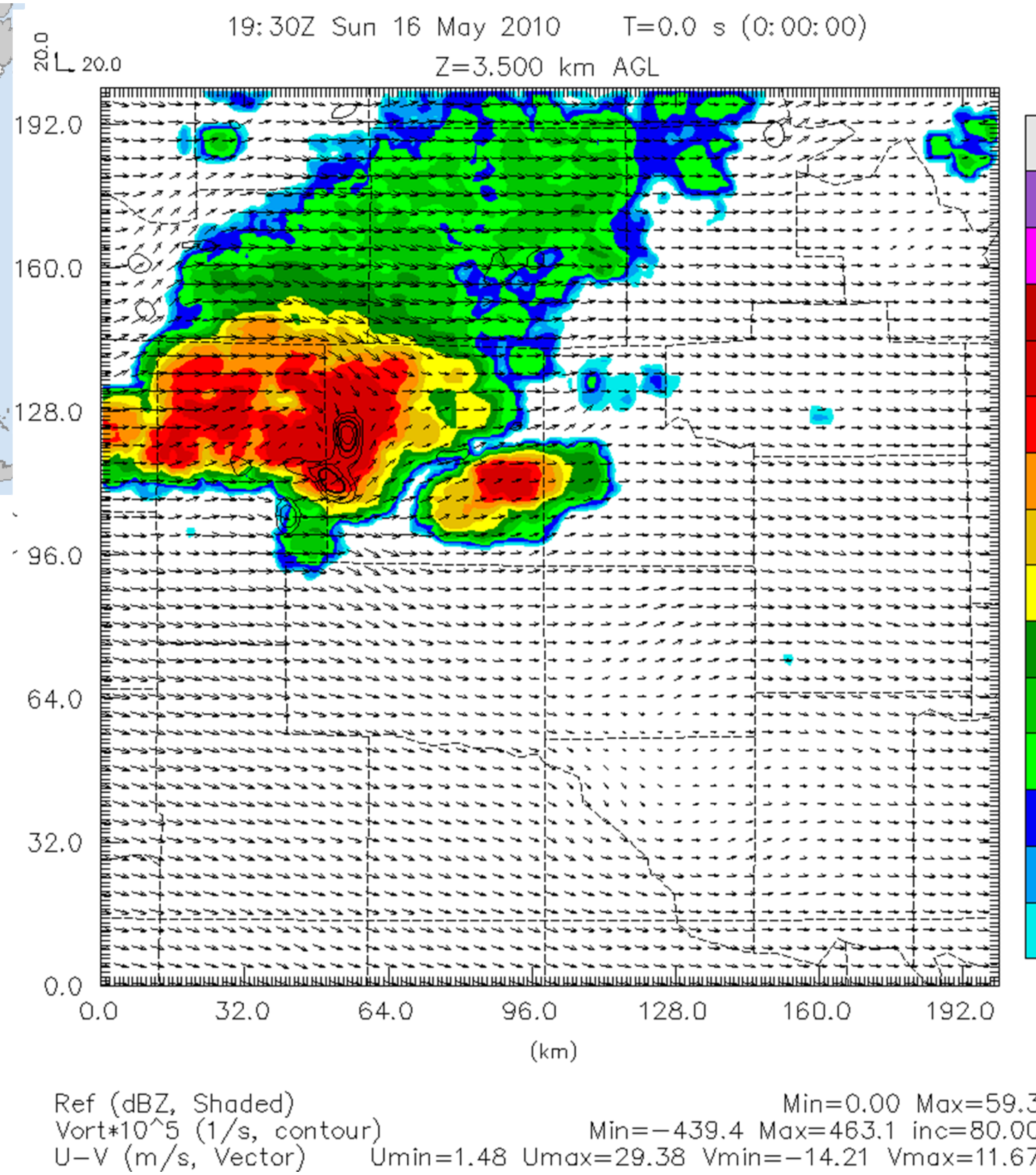




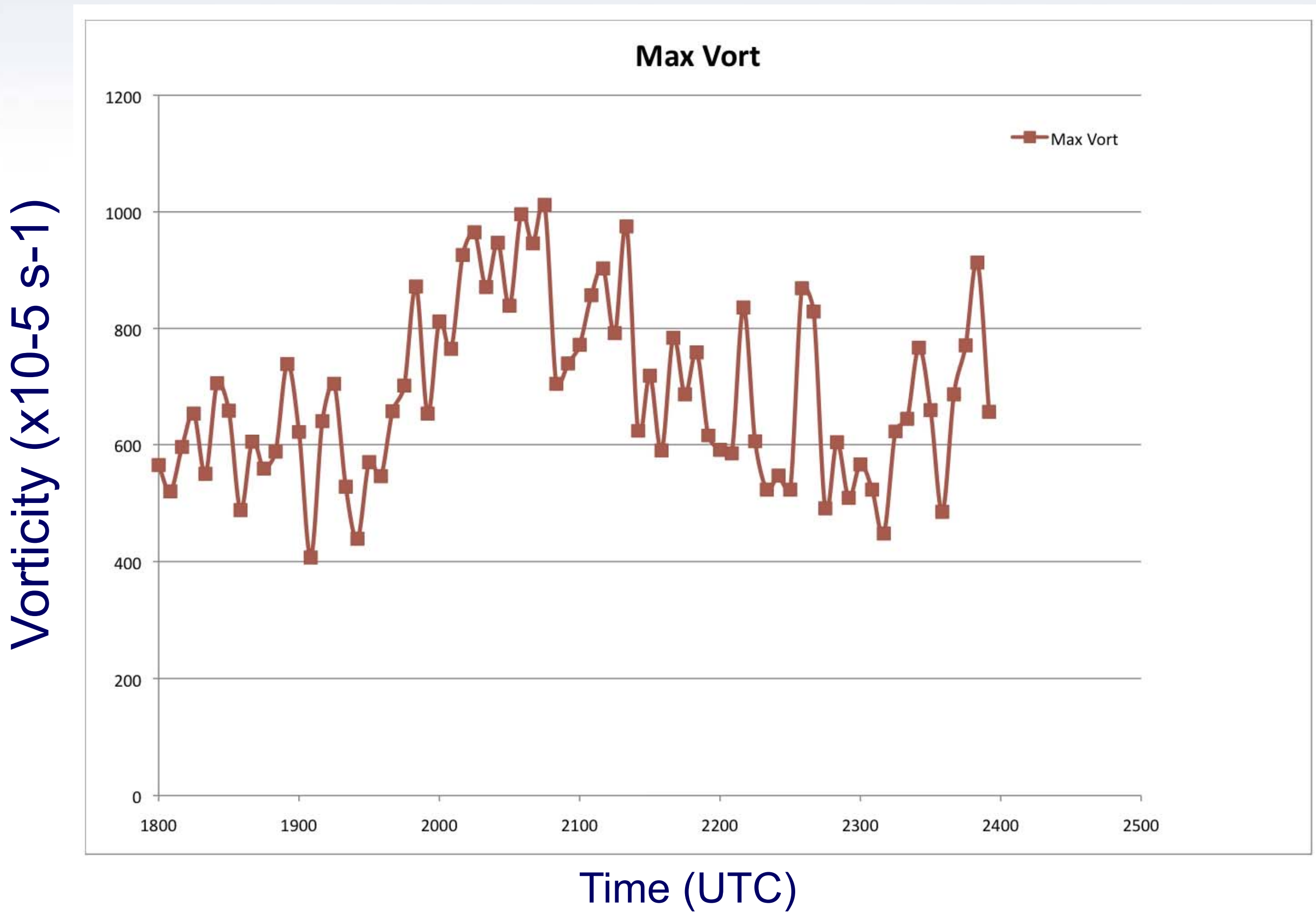
May 16th OKC metro Hailstorm





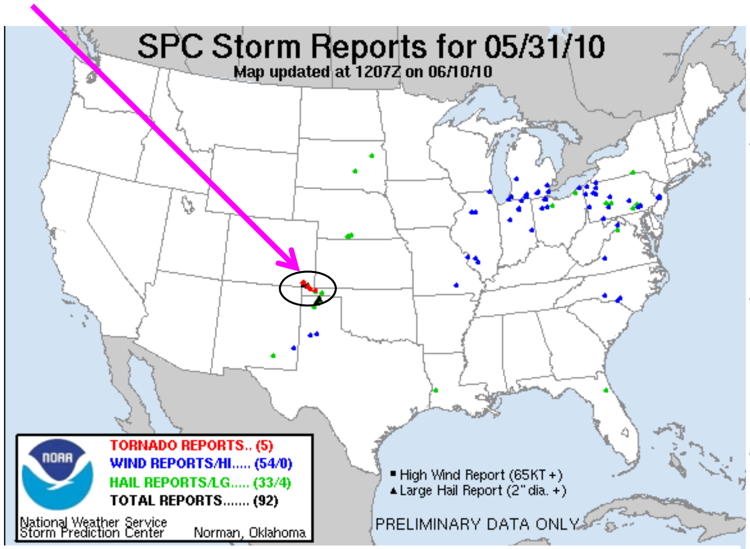


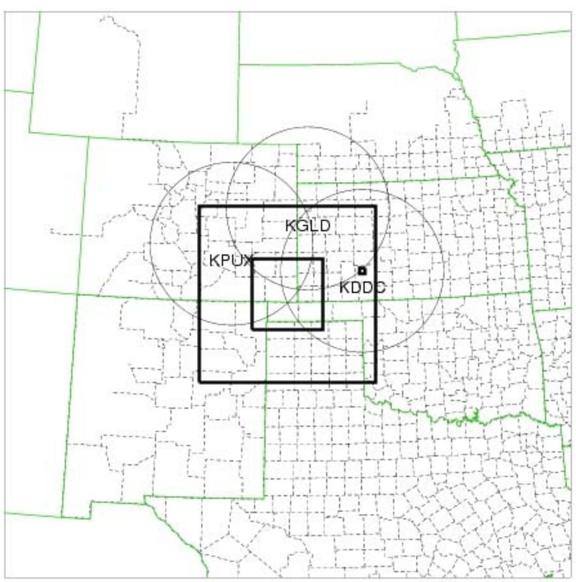
May 16th OKC Metro Hailstorm

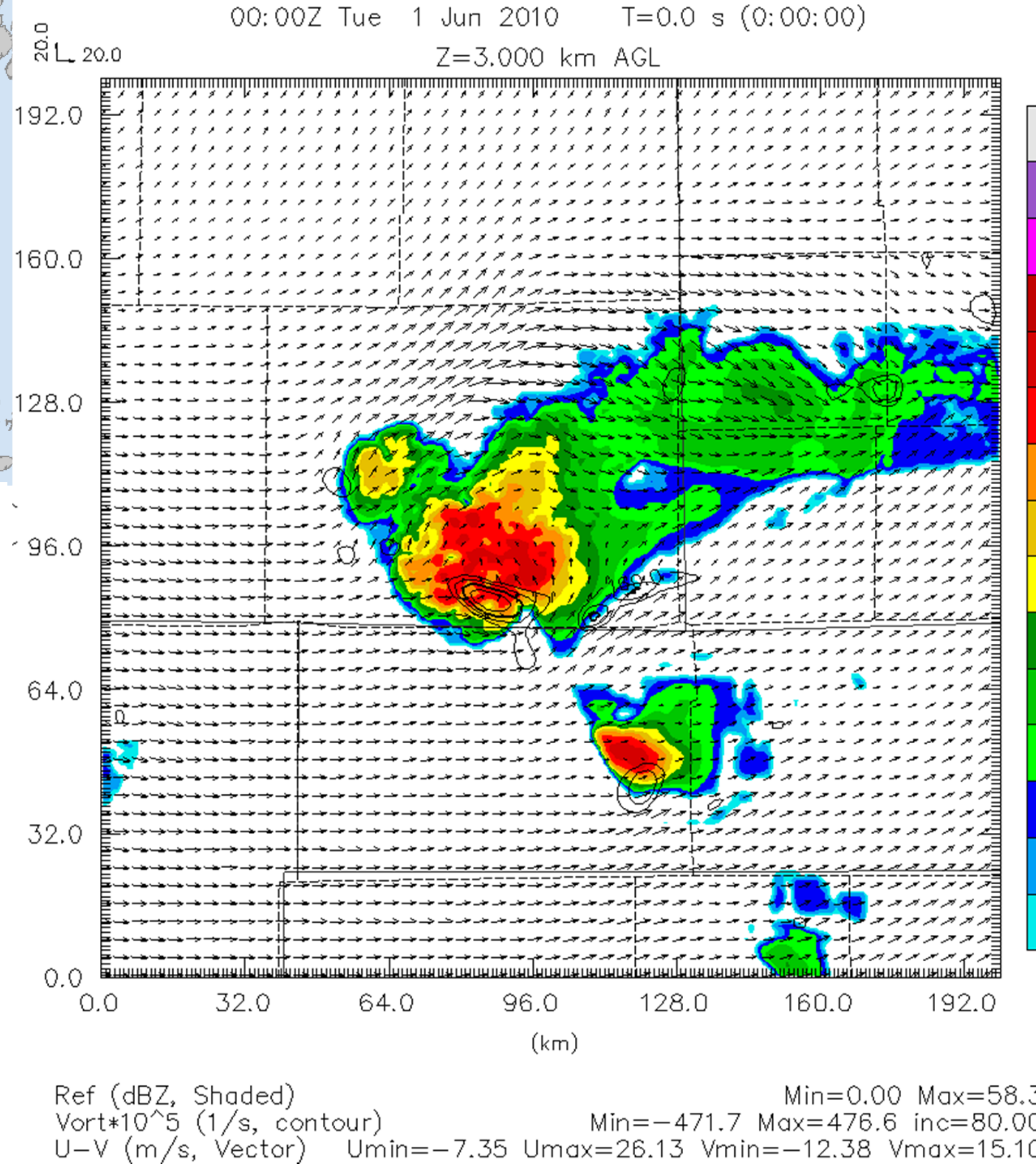


Vorticity throughout 3-7 km layer also is very consistent.

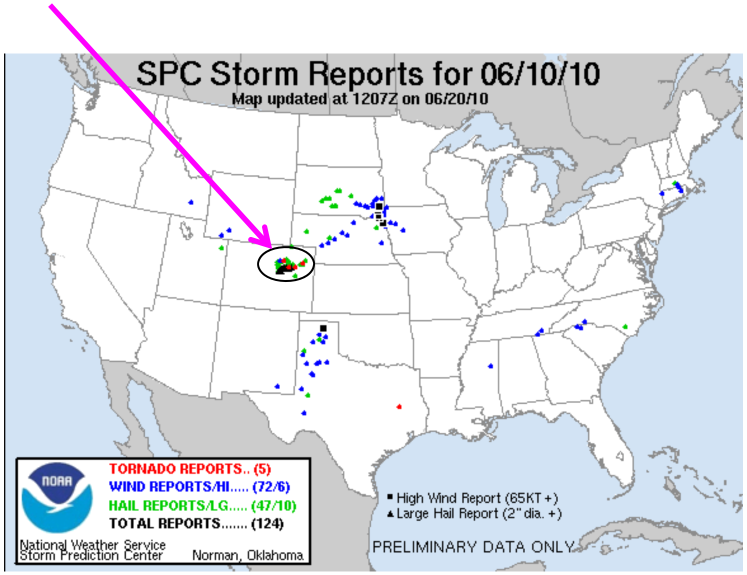
May 31th Okla. Panhandle Tornado

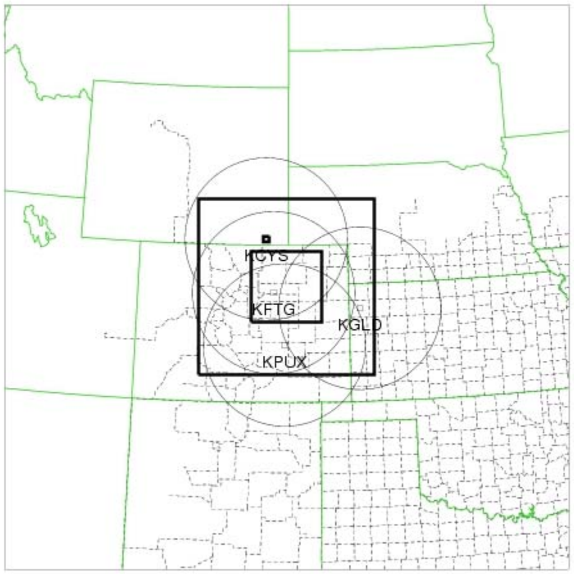


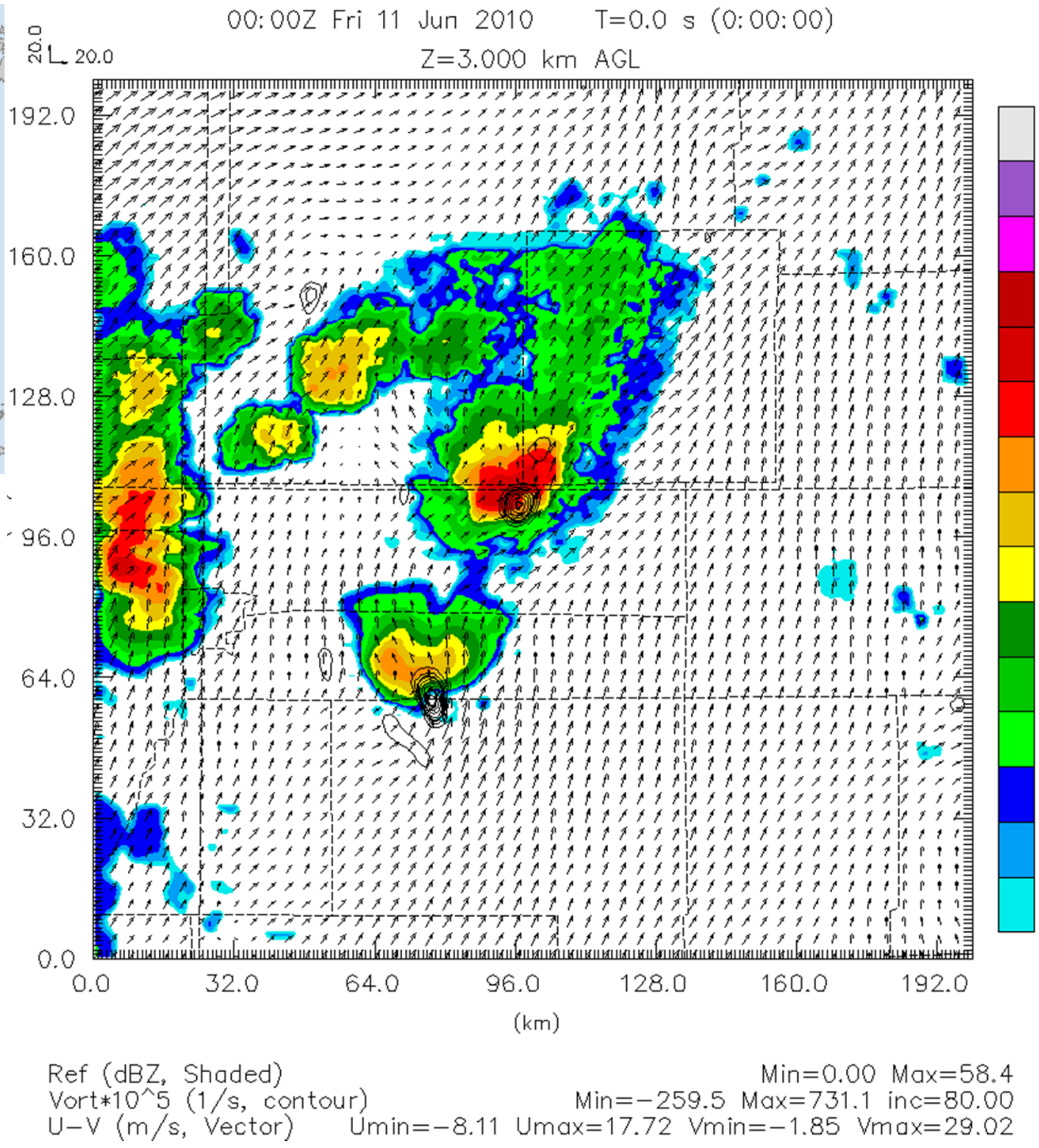




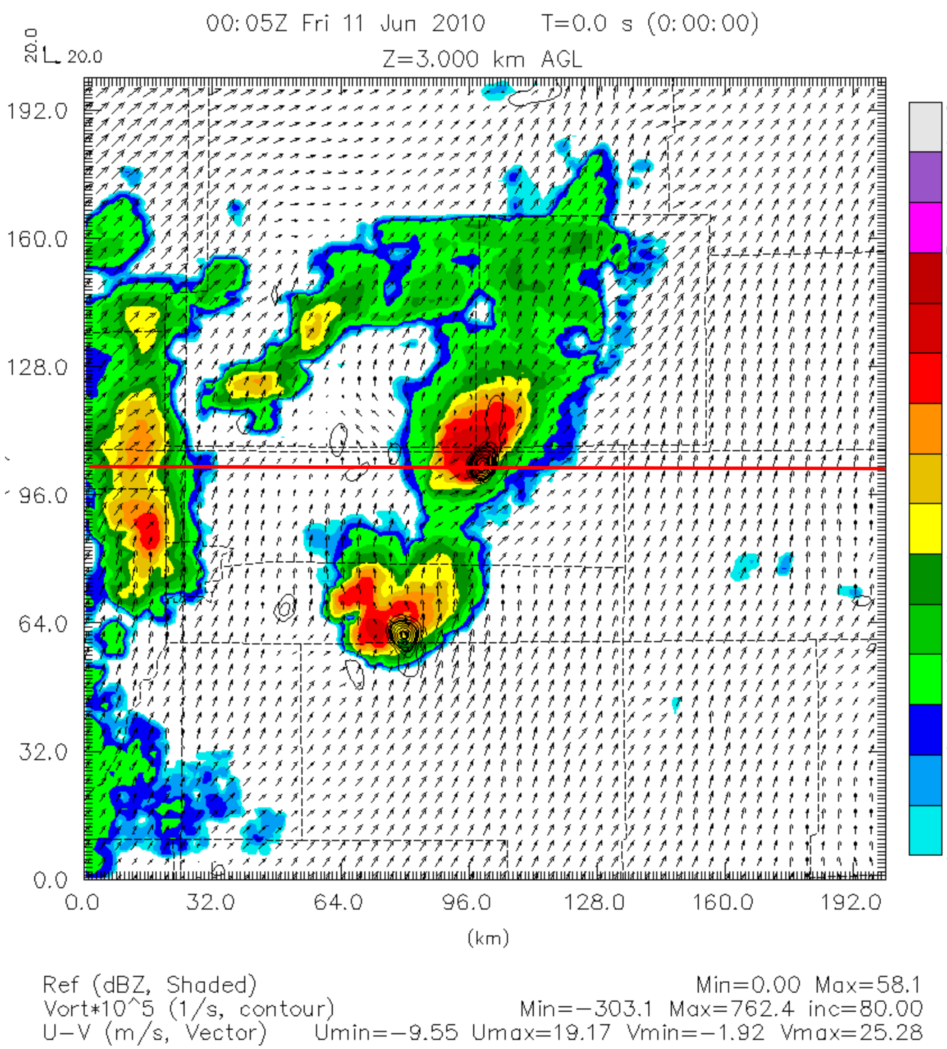
June 10th CO Tornadoes

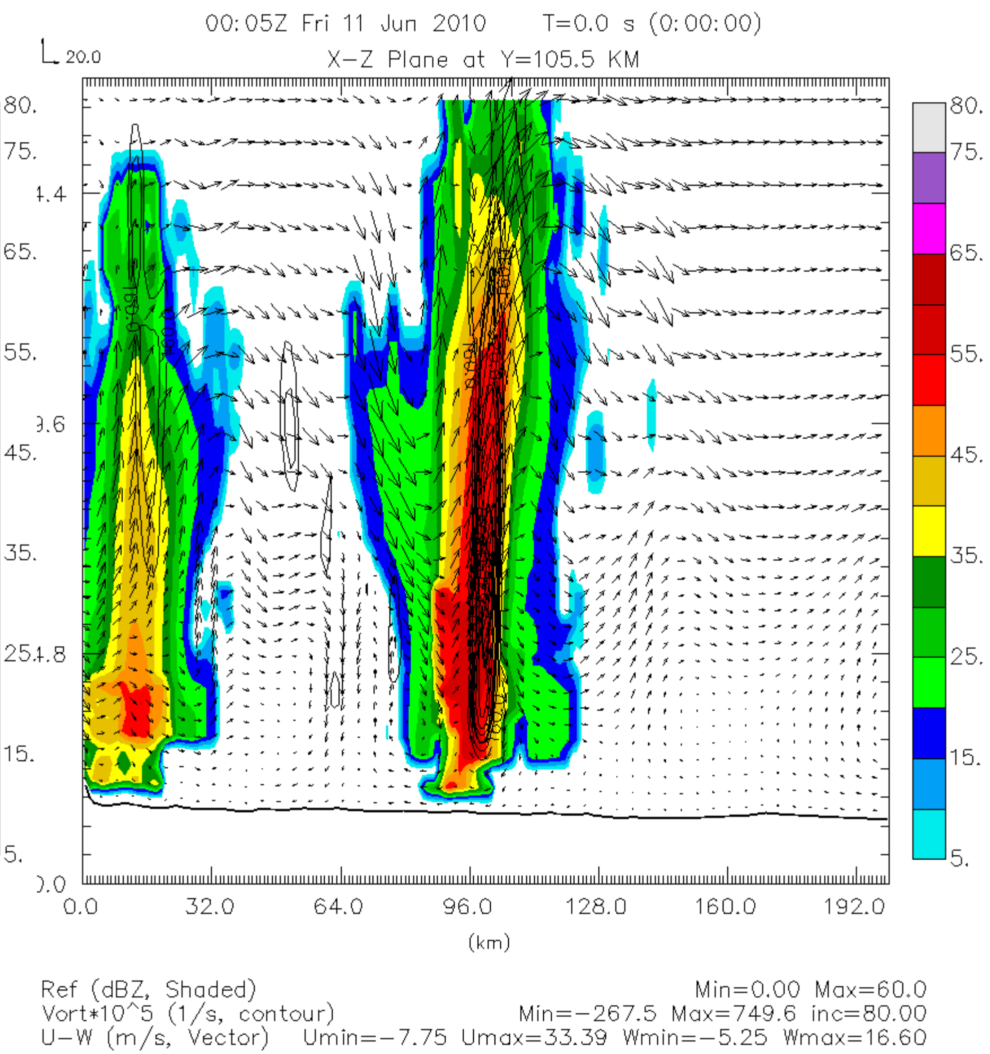




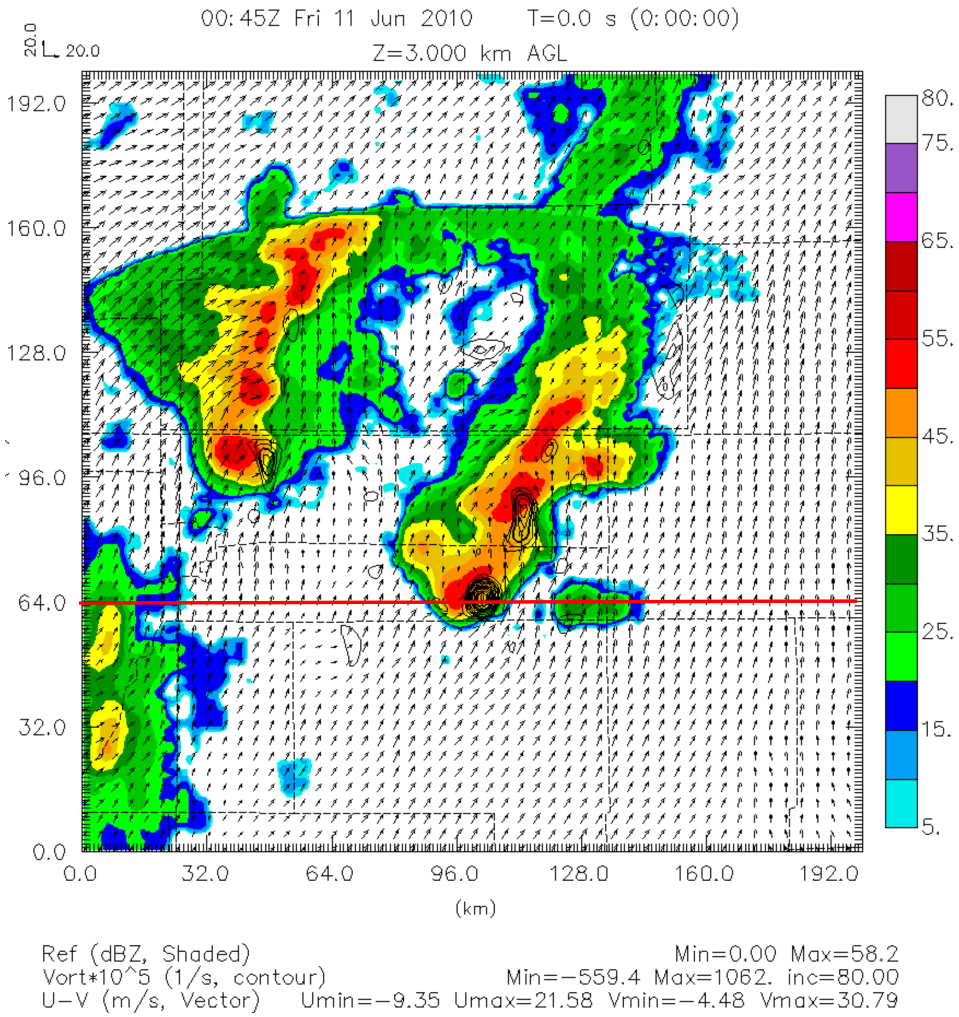


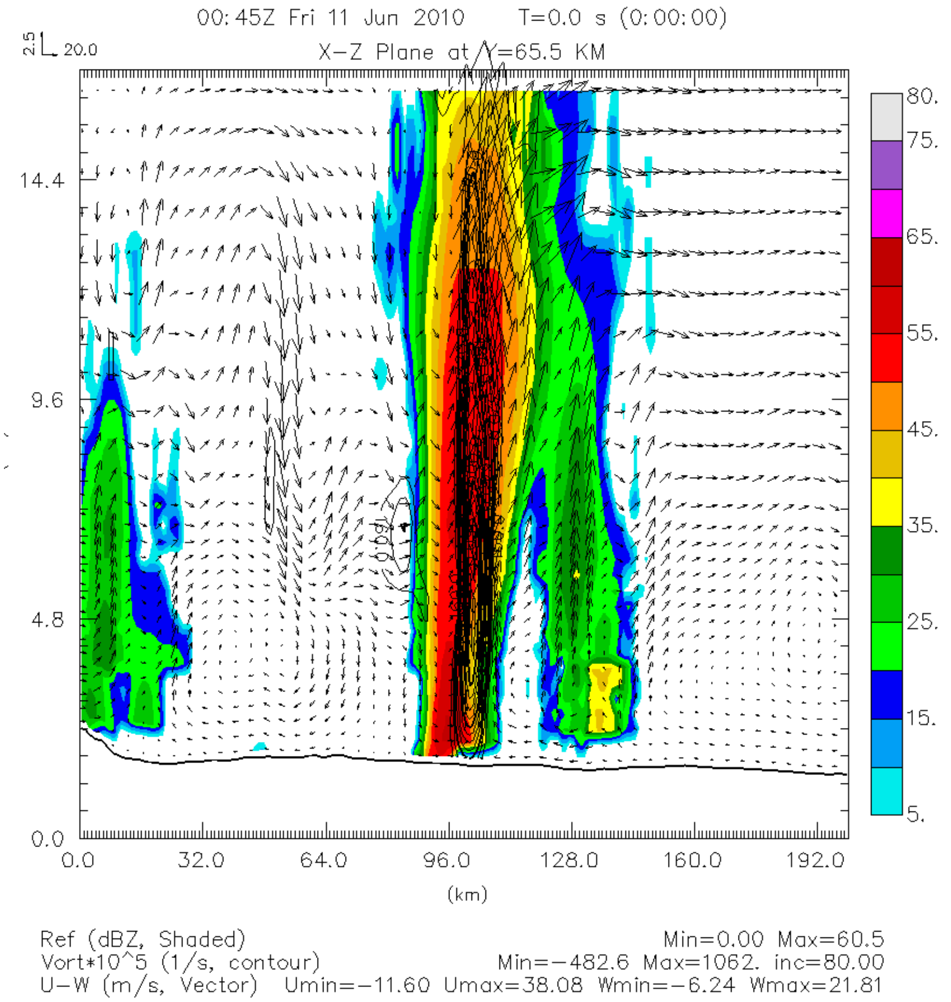
June 10th CO Tornadoes (Con'd)





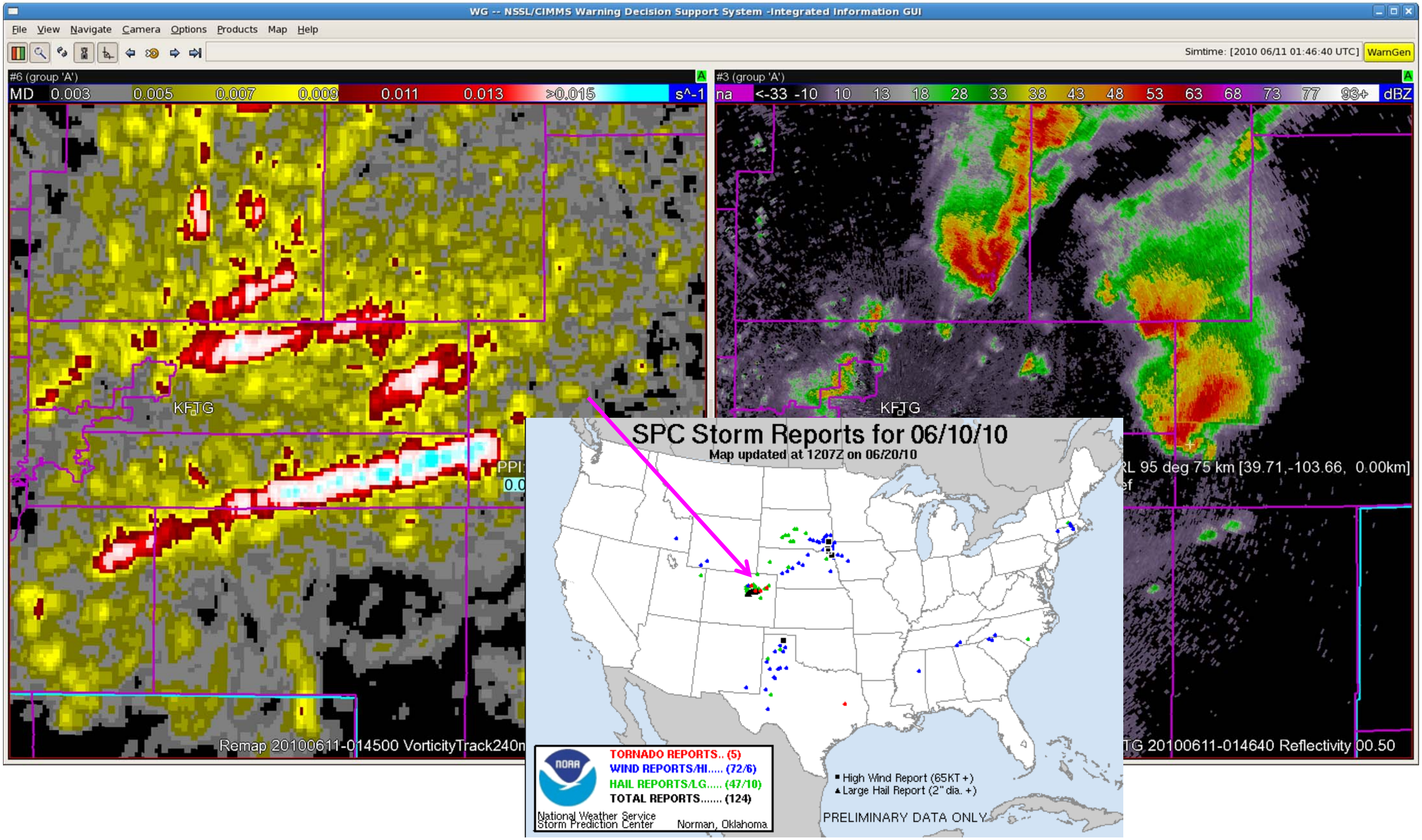
June 10th Colorado Tornadoes (Con'd)





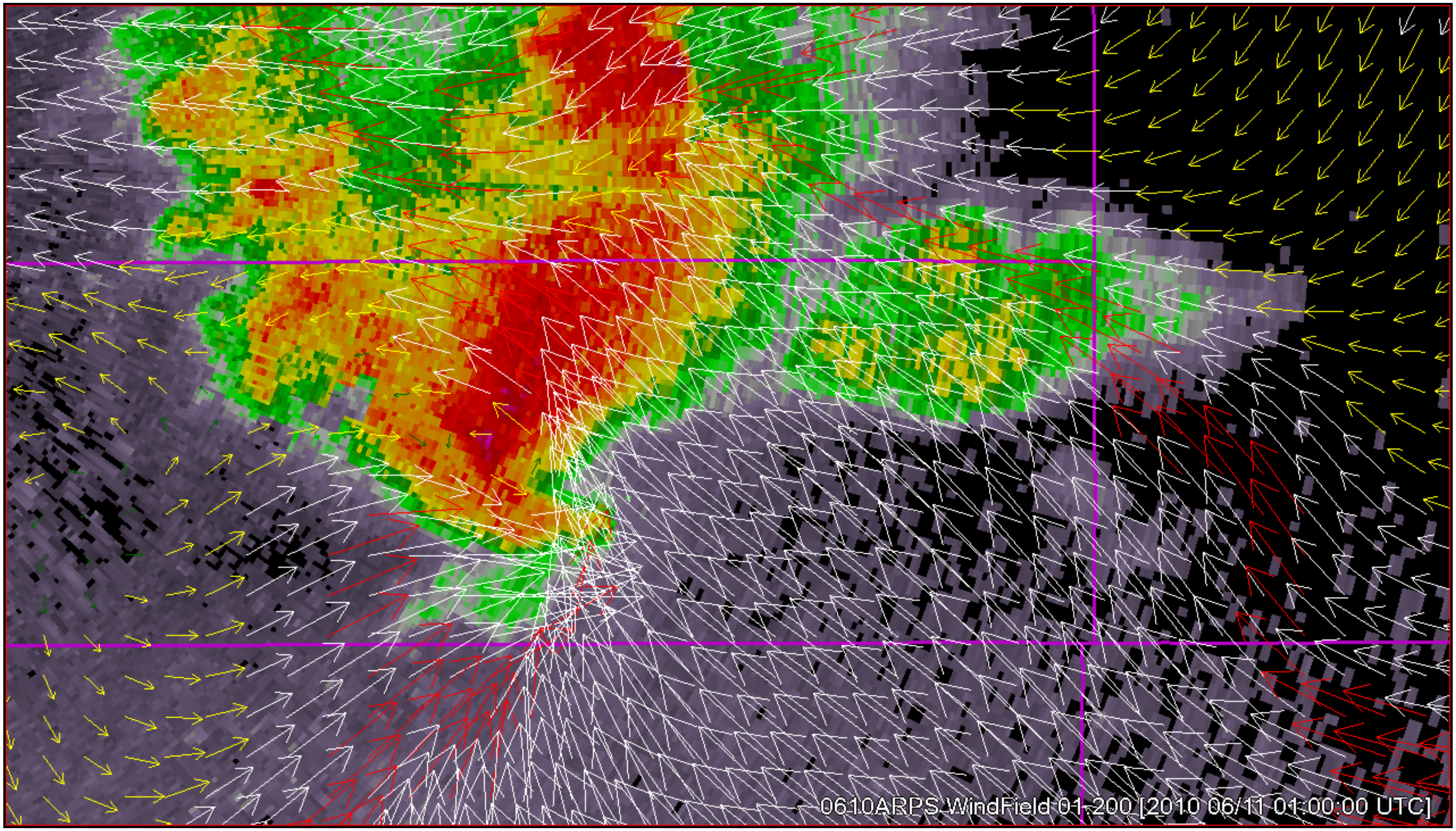
June 10th CO Tornadoes (WDSS-II Displays)

Composite Vorticity Track   Reflectivity at 1.5^{0}



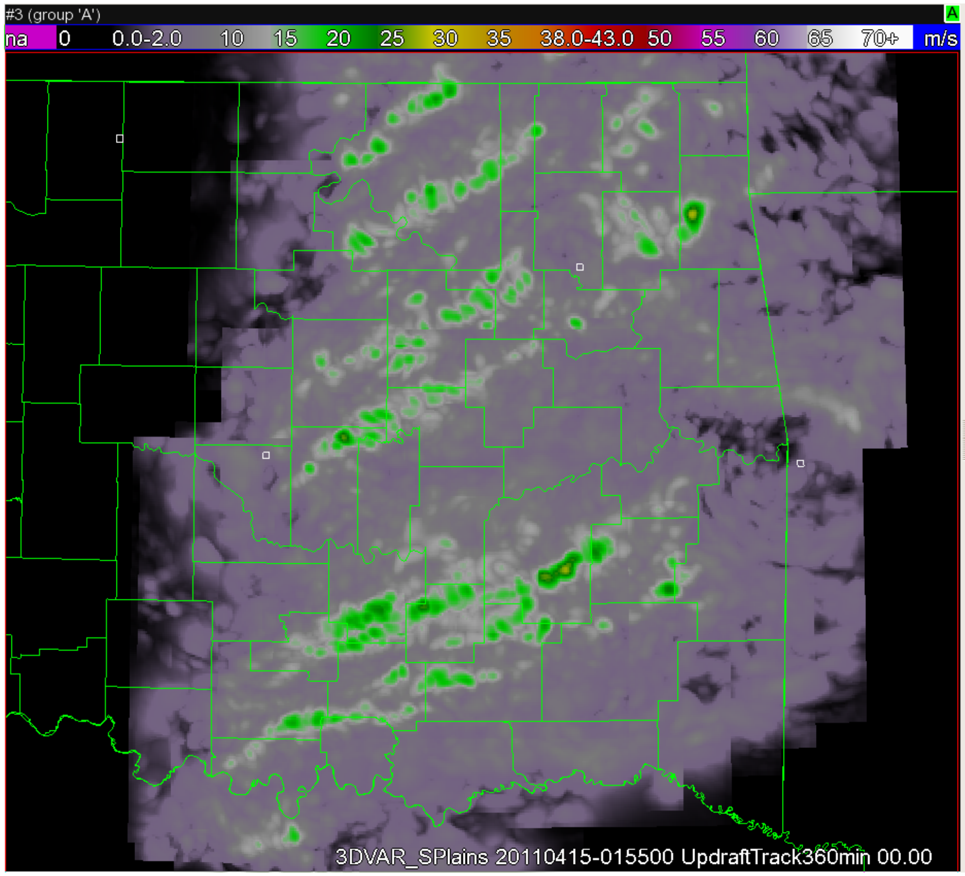
June 10th CO Tornadoes (WDSS-II)

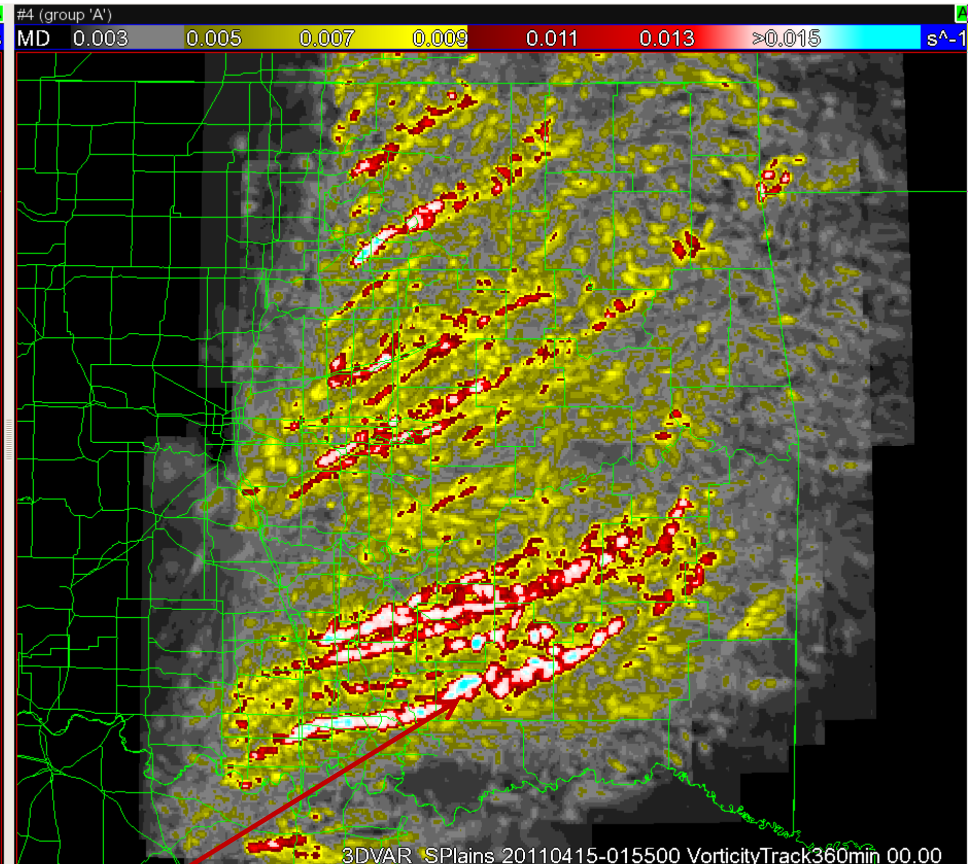
Wind Vectors near surface overlaid with Z at 0.5^0



0100 UTC

April 14th, 2011 East OK Tornado Events (3DVAR products)



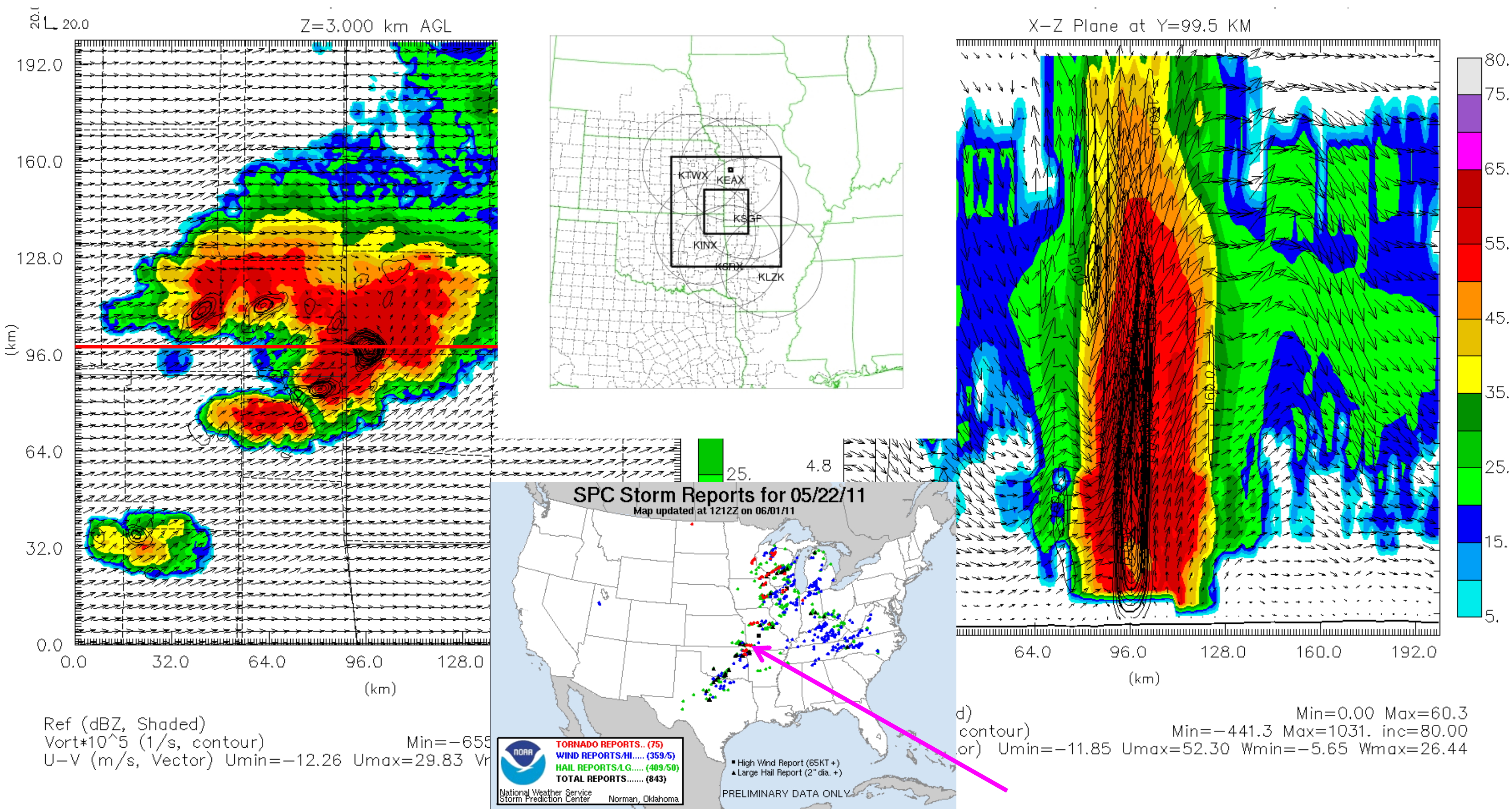


Storm track of w

Tushka, OK

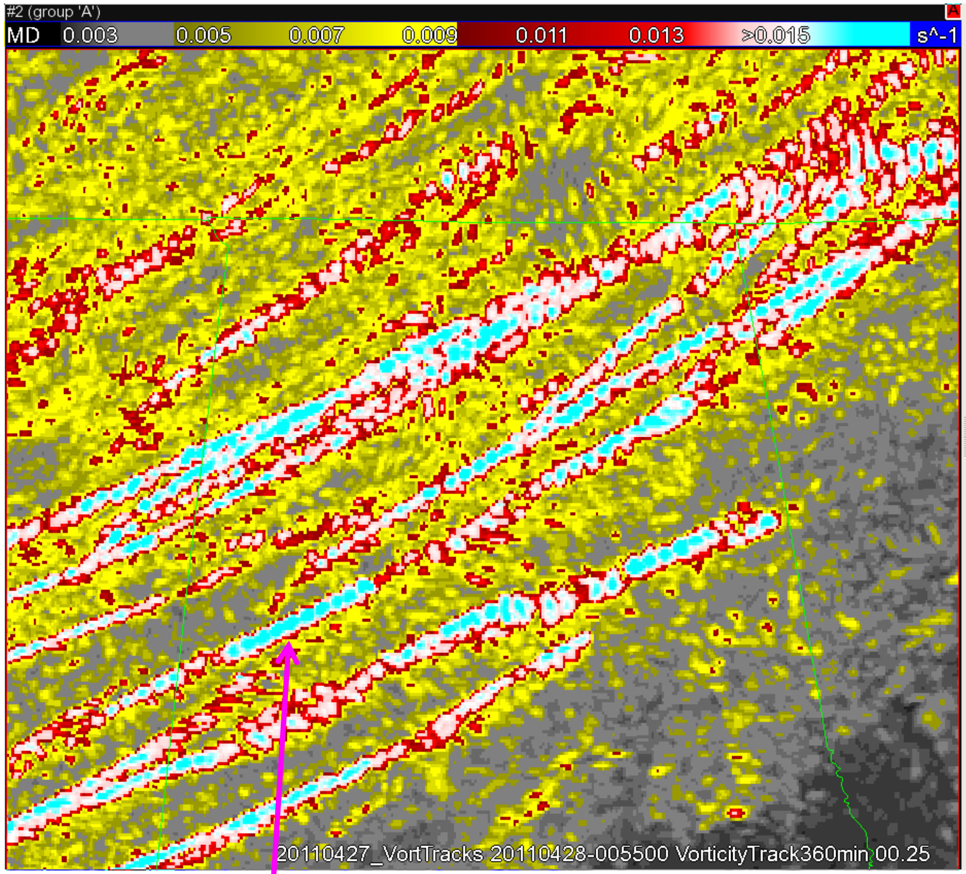
Storm track of vertical vorticity

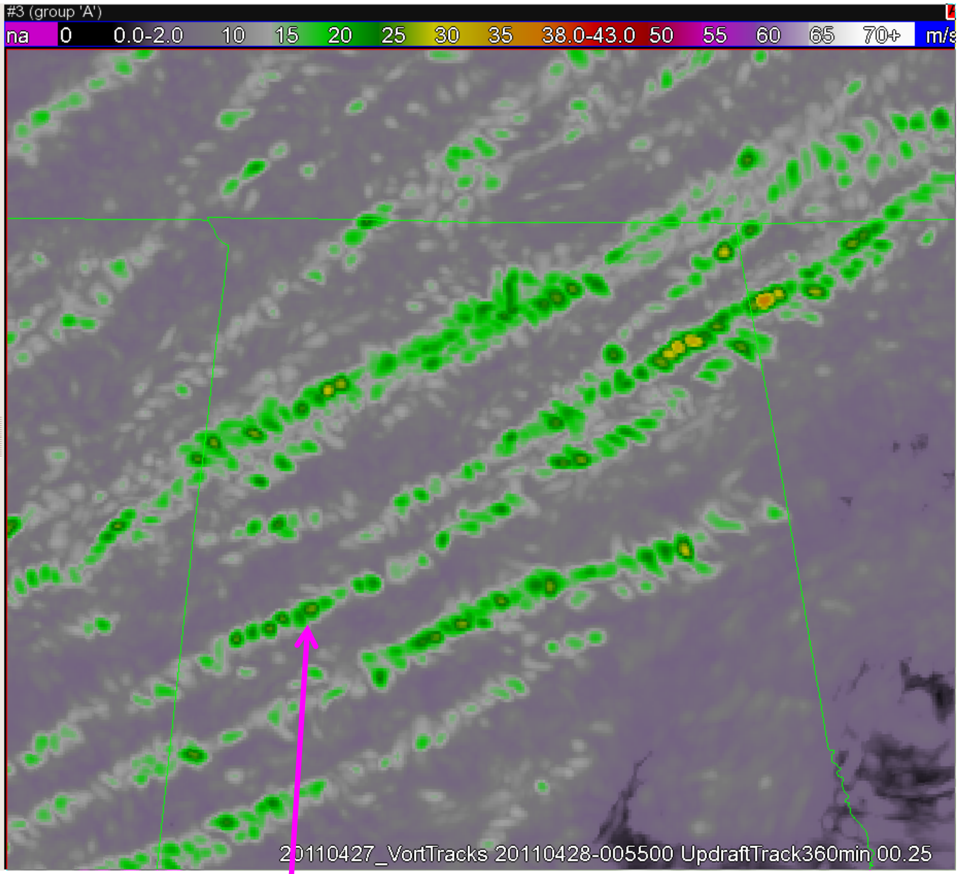
May 22th Joplin/MO Tornadoes



http://www.nssl.noaa.gov/users/jgao/public_html/analysis

Apr 27th 2011 South Plain Tornado Outbreak 3DVAR off-line products (with a 1200x1000 km domain)





Tuscaloosa

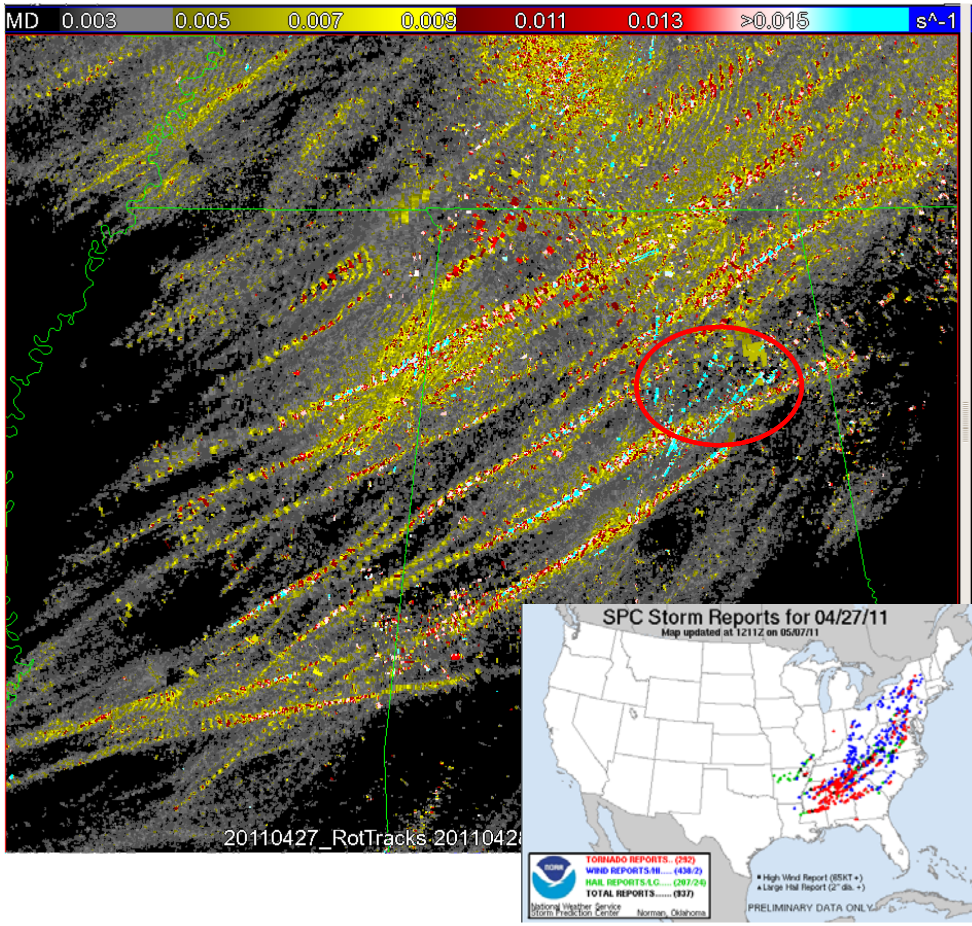
361 people died in 7 states

Tuscaloosa

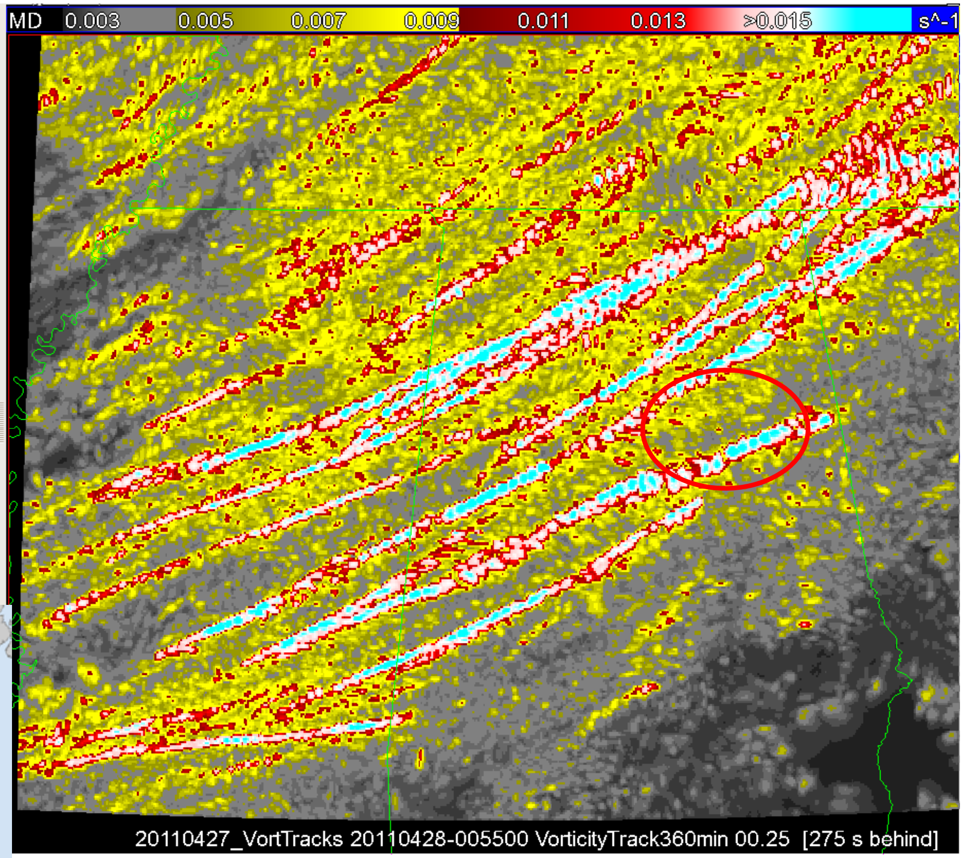
Storm track of composite vorticity

Storm track of w

Apr 27th 2011 South Plain Tornado Outbreak (Comparison of NSSL MRMS and 3DVAR product)



Shear-derived vorticity tracks from NSSL MRMS system



Vorticity tracks derived from 3DVAR products

Summary for Realtime 3DVAR Application

(a) A realtime weather-adaptive 3DVAR system to help forecasters identify meocyclones;

(b) Automatic storm detection using WDSS-II product;

(c) Capability of on-demand user-defined domain;

(d) Produce with 1 km resolution every 5 min.

Application: tested in EWP/HWT spring experiments in WAG/NSSL for Spring of 2011.

Feedback: NWS forecasters: “It definitely improves my confidence to issue severe weather threats”.

II. Research Challenges & Future Work

1) The major issue for 3DVAR is no flow-dependent background error covariance. We are trying to reduce the impact with equation constraints, but it still needs a lot of work.

2) For EnKF, model error may play a big role for real data case. Need detail comparison of EnKF and 3DVAR when model error is significant.

3) Do we need QC for different radar operational mode? How to solve the problem of radar data boundary?

4) To add the TDWR radar network to 88D network may provide a little help (low-hanging fruit).

4) For reflectivity assimilation:

- The forward operator is nonlinear;
- Different microphysics may give you a different versions of reflectivity operators;
- Low values of reflectivity is more sensitive to obs error.

5) It is difficulty to demonstrate hybrid EnKF-3DVAR is better than pure EnKF. More work is needed.

6) How to assimilate the Dual-Pol data into NWP model in variational framework.